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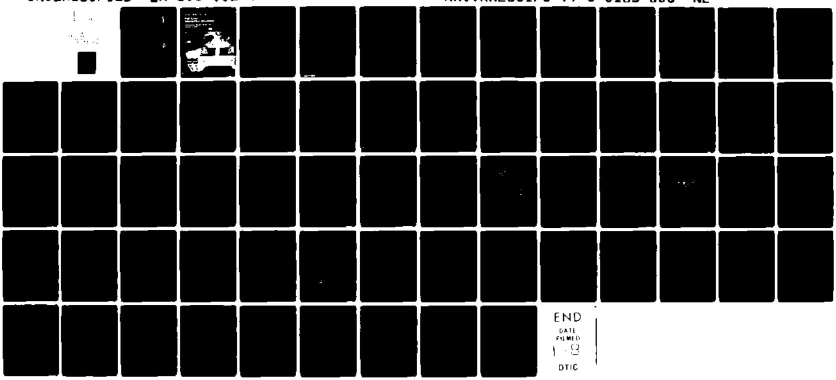

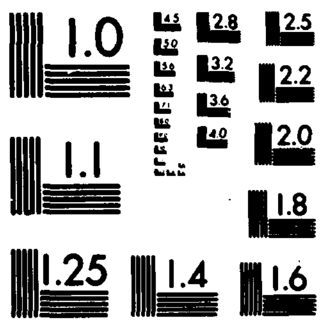

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Volume IV: Motion

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Design Definition Study Report

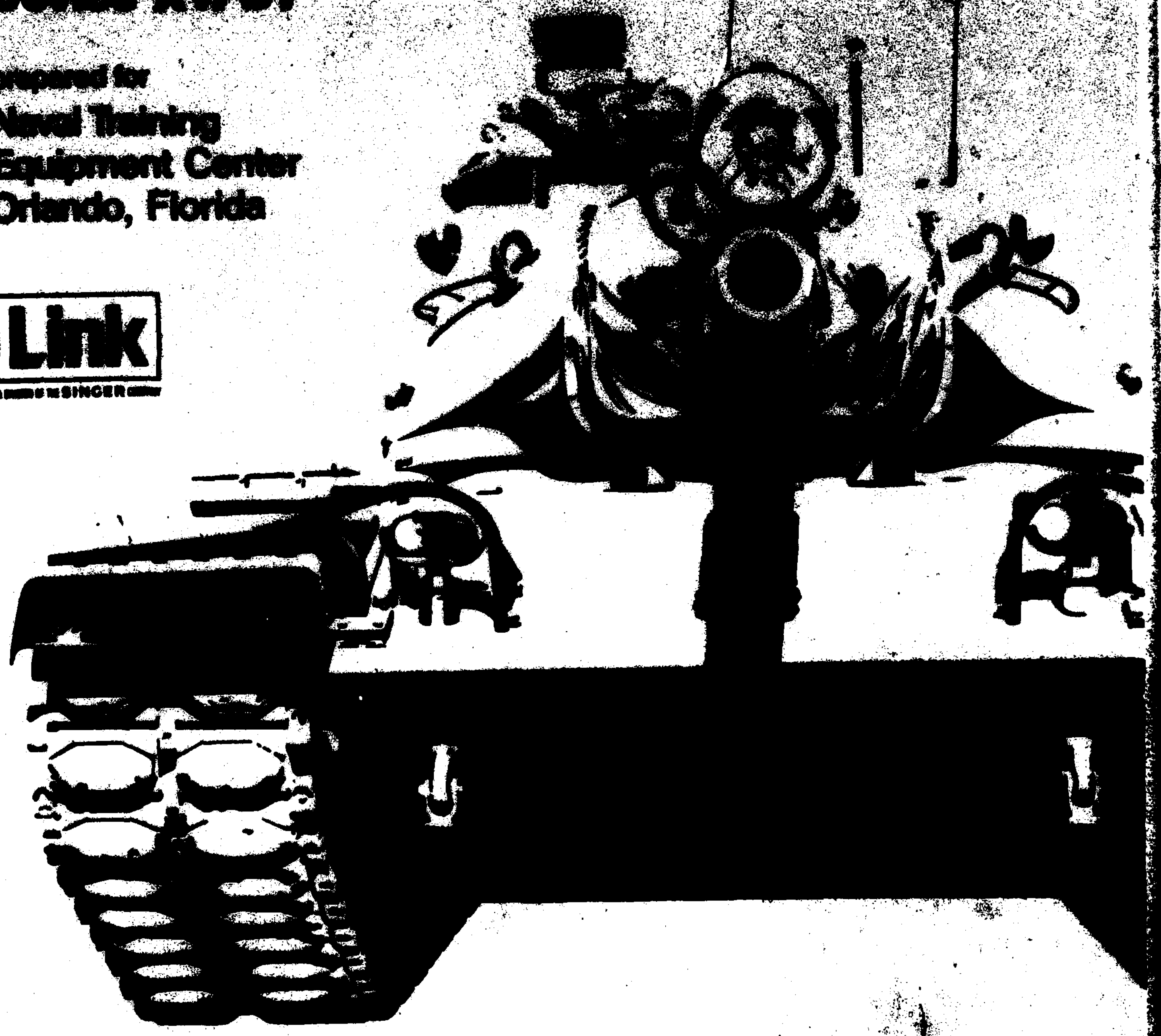
Full Crew Interaction Simulator

Laboratory Model (FCIS-LM) Device X17B7

prepared for

Naval Training Equipment Center
Orlando, Florida

Link
A DIVISION OF THE SINGER COMPANY



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LR-895

DESIGN DEFINITION STUDY REPORT

FULL CREW INTERACTION SIMULATOR-LABORATORY MODEL

(DEVICE X17B7)

VOLUME IV - MOTION

Link Division, The SINGER COMPANY
Binghamton, New York 13902

FINAL
JUNE 1978

Prepared for:
NAVAL TRAINING EQUIPMENT CENTER
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TABLE OF CONTENTS

VOLUME IV

LIST OF TABLES

VOLUME IV

LIST OF ILLUSTRATIONS

VOLUME IV

SECTION IX

9. MOTION AND DYNAMICS STUDY AND CONCEPT FORMULATION

9.1 Vehicle Dynamics

The Link Division of The Singer Company has extensive experience in vehicle dynamics — including ground reactions for takeoff and landing of flight simulators. In addition to this experience, the Link-Miles operation in the United Kingdom has built a variety of tracked-vehicle driver trainers (though not for the United States).

A detailed research effort was initiated to determine vehicle dynamics peculiarities and state-of-the-art as related to tank mobility.

9.1.1 Equations of Motion. The major research efforts considered and evaluated research by:

1) Systems Research Group, Ohio State University
2) U.S. Army Tank-Automotive Research and Development Command
3) Roy D. McKenzie, et al at GM Defense Laboratories
4) M. G. Bekker (various texts)
5) Link-Miles

Research efforts 1, 2, and 3 discuss engineering simulations as opposed to real-time training simulations. Link-Miles research deals with real-time training simulation design; therefore, each design evaluation was based on the complexity and its specific purpose. The Link-Miles design also includes a camera-model visual system interface.

The cited research efforts and the individual approaches will be described in order of decreasing complexity.

The McKenzie approach has been referred to, by M. G. Bekker, as the most general approach since it includes inputs for the geometry of mass distribution of the vehicle, suspension and power train characteristics, terrain surface contours, soil values, and driver's characteristics. The equation implemented by McKenzie for soil thrust (maximum thrust the soil can sustain) is:

$$T_{max} = (A \cdot c + W \cdot \tan\phi + \Delta T') \cdot f(slip)$$

Where:

A	=	Track/ground contact area	~ $inches^2$
c	=	coefficient of cohesion of soil	~ psi
W	=	vehicle weight	~ lb
ϕ	=	angle of soil friction	~ degrees
$\Delta T'$	=	the additional shearing force produced by the grousers on the track.	
$f(slip)$	=	monotonic function of slip	

The equation for $\Delta T'$ is:

$$\Delta T' = 0.64 \left(\frac{h}{b} \cdot \text{arcctn}\left(\frac{h}{b}\right)\right)$$

Where:

h	=	grouser height	~inches
b	=	track width	~inches

The above equations are also as suggested by M. G. Bekker. The track slip function proposed by McKenzie and later by Bekker is:

$$f(slip) = \left[1 - \frac{1}{j}\left(1 - e^{-j}\right)\right]$$

Where:

$$j = \frac{i \cdot L}{k}$$

$$i = \frac{v_t - v_v}{v_t}$$

and:

v_t	=	speed of the track	~inches/sec
v_v	=	speed of the hull	~inches/sec
L	=	length of the contact area	~inches
K	=	slip coefficient	~inches

As mentioned in Section 3.1.2, a portion of the vehicle thrust is required to overcome the motion resistances. In particular; let T_{req} be the thrust required to just initiate and to maintain motion. The following resistances are summed in order to calculate T_{req}:

a) Resistance due to vertical displacement of soil - assuming that the ground compressed by the track moves only vertically, the compaction resistance per track is:

$$R_c = \left(\frac{k_c + b \cdot k_{c\phi}}{n+1}\right) \cdot z^{n+1}$$

Where:

b	=	width of the track/ground contact area	~ inches
k_c	=	modulus of soil deformation due to cohesion	~ $lb/(in)^{n+1}$
k_ϕ	=	Modulus of soil deformation	~ $lb/(in)^{n+2}$
n	=	exponent of soil deformation	~ dimensionless

On the level ground, the static ground sinkage is:

$$Z = \left[\frac{W}{L\ (k_c + b \cdot k_\phi} \right] \frac{L}{n}$$

b) Resistance due to forward displacement of soil - Bulldozing resistance or passive pressure resistance on the front of the track due to the pushing of a substantial soil mass may be estimated by:

$$R_b = \frac{b \cdot \sin(\alpha+\phi)}{\sin \alpha \cdot \cos \phi} \cdot c \cdot Z \cdot K_c$$

Where:

$$K_c = (N_c - \tan \phi) \cdot \cos^2\phi$$

and α is the angle of approach for a track vehicle, and N_c a Terzaghi bearing capacity factor.

c) Grade Resistance - Motion resistance due to slope is:

$$R_g = W \cdot \sin \theta$$

where θ is the inclination angle of the terrain.

d) Air Resistance - Power loss due to aerodynamic drag.

e) Inertia Resistance - Every change of speed of a vehicle is opposed by a so-called "inertia" force which is always directed against the vector of acceleration.

f) Vegetation Resistance - The effect of vegetation on vehicle motion.

The McKenzie approach is primarily directed toward the translational, rather than the rotational equations of motion. In particular, rotational acceleration and velocities of a tracked vehicle as the vehicle follows the contour of the terrain were not discussed. To implement the McKenzie approach, a large quantity of data is required. Specifically; sinkage would change as a function of the inclination angle of the terrain and the type of soil, and ground pressure would vary from the static relationship P = W/A to become a function of the velocity of the tracked vehicle.

William H. Perloff (Systems Research Group) described three approaches available to him at the time of his work. He concluded, however, that none were acceptable and developed his own approach. Figure 9-1 illustrates the effects of sinkage on the surface inclination and the types of soil as determined by Perloff. In particular, Z_f is the sinkage at the front end of the tracked vehicle and β-i (Beta minus i) the tank inclination relative to the ground surface. Perloff's approach would not be acceptable for real-time simulation since it involved iterative solutions. An ideal approach would be to re-define McKenzie's equations in order to use them together with the off-line data generated using Perloff's approach. However, it is believed that computer core and time would be substantial.

F.B. Cook and W. Snowball (Systems Research Group) generated an approach designed to calculate the translational acceleration of a tracked vehicle in a situation where the effects of soft soil (track slip and sinkage) and rough terrain (vibration loading of the crew) are negligible. This approach is also described by M. G. Bekker. Cook and Snowball determined the total resistance of motion to be composed of two additive components: rolling resistance R_r, and grade resistance R_g. The latter has been previously defined. Rolling resistance includes such factors as aerodynamic resistance, mechanical friction in the track and final drive gearbox, and track-slip resistance, and is given as:

$$R_r = f_o \cdot W$$

Where f_o is the coefficient of rolling resistance, empirically determined in tow tests for particular road surfaces and existing tracked vehicles. The coefficient of rolling resistance is a function of the speed of the tracked vehicle. Vehicle equivalent mass, which is used to account for the acceleration of rotating masses within the vehicle, is:

$$M = \frac{W}{g}\left[(1+a) + 0.0025\varepsilon^2\right]$$

Where:

g	=	gravitational constant	~ (ft/sec^2)
a	=	equivalent mass factor for the track	~ dimensionless
ε	=	gear reduction between the engine and drive sprocket	~ dimensionless

The soil thrust or maximum tractive force that the surface can mobilize to propel the vehicle is:

$$T_{max} = \mu \cdot W \cdot \cos\theta$$

Where μ is the coefficient of friction. If the tractive force produced by the power plant is T and $T > T_{max}$, then the transla-

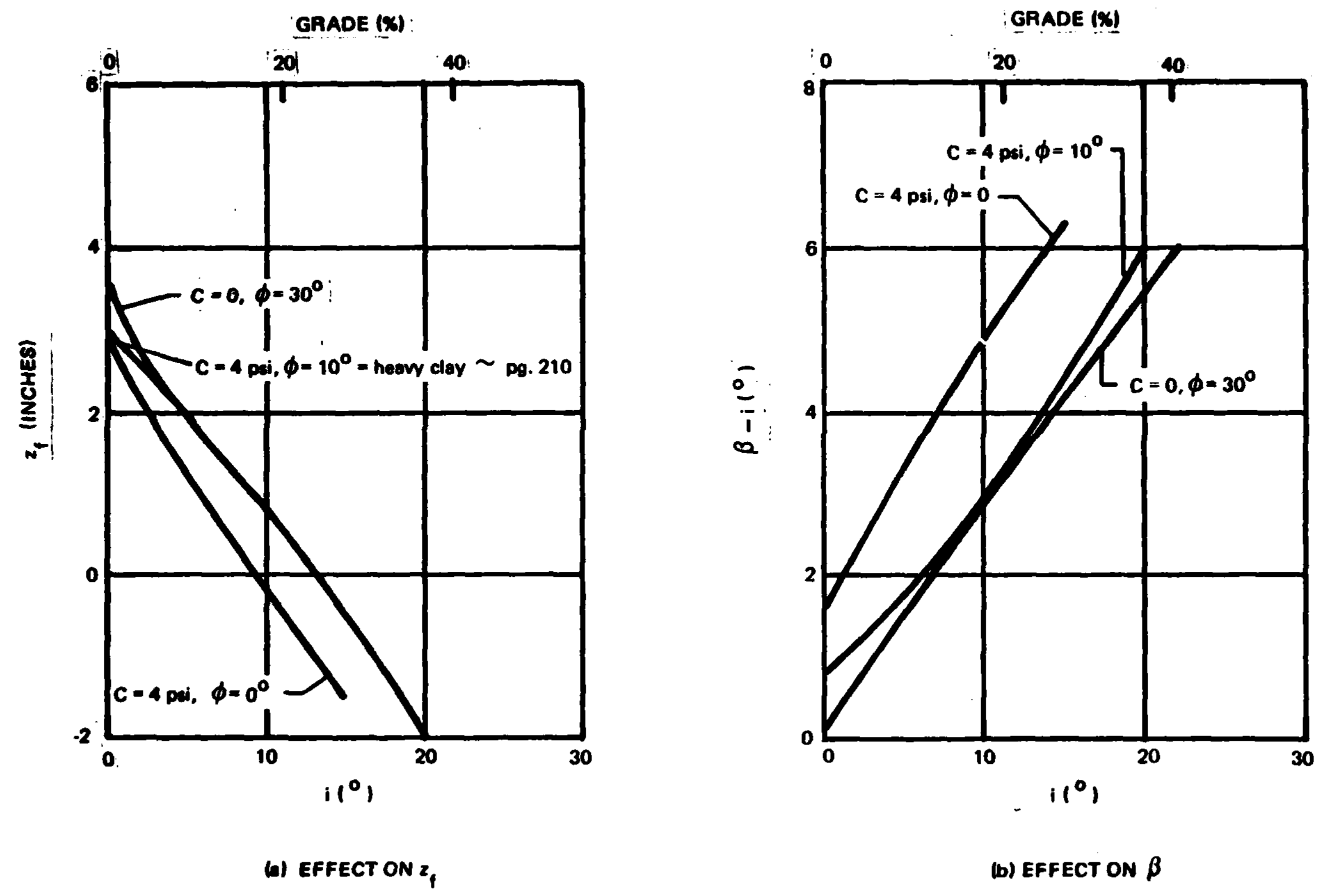

Figure 9-1 Effect of Ground Surface Inclination i, on Z_f and β for three soils

tional acceleration of a tracked vehicle is limited to:

$$A = T_{max} - R_g - R_r = \left[\frac{u \cdot W \cdot \cos\theta - W \cdot \sin\theta - W \cdot f_o}{(W/g) \cdot \quad (1+a) + 0.0025 \cdot \varepsilon^2}\right]$$

$$= g\left[\frac{W \cdot \cos\theta - \sin\theta - f_o}{(1+a) + 0.0025 \cdot \varepsilon^2}\right]$$

This approach is simple, though constrained by the simplifying assumptions as previously stated, and can easily be implemented in a real-time simulator.

The AMC '74 Mobility Model (U.S. Army Tank-Automotive Research and Development Command) is also an engineering simulation applicable to wheeled and tracked vehicles. This model uses the coefficient of cohesion of soil and the angle of soil friction to define the mobility of the soil-vehicle system.

The Link-Miles approach uses a coefficient of friction and rolling resistance in their translational equation of motion. As stated previously, the Link-Miles approach is used in a real-time driver trainer integrated with a camera model visual system. However, the coefficient of friction is not correlated with the terrain directly beneath the tank, but rather, is a function of instructor inputs; specifically, zero for dry and one for wet conditions. Although it would be difficult to correlate the coefficient of friction of the terrain underneath the tank using a camera-model visual system, the correlation would be available using a DIG visual system. Rotational equations of motion, follow in a scaled manner, the accelerations, velocities, and attitude of the model board orientation transducer as it traverses across the model board. Specifically, calculation of moments and moments of inertia is not required since rotational motion is dictated by the transducer.

9.1.1.1 Approach to Equations of Motion. The major approaches investigated during the study were previously highlighted. FCIS crew training requirements, discussed in Section 5, dictate the approach used for equations of motion. The primary purpose of the FCIS is to train each of the crew members to perform their respective tasks as an integral part of a team in a tactical situation. Attitude and velocity fidelity are considered important with respect to the chosen equations of motion concept. Velocity fidelity is referred to as the changes in velocity as a function of the simulated terrain/soil condition.

beneath the tank. Therefore, the following simplifying assumptions with respect to simulated tank translational motion can be made:

1) The effects of soft soil, i.e., track slip and sinkage are negligible.

2) Predominantly friction type soils are considered.

3) The effects of the grousers on the track are considered negligible.

The above assumptions effect the soil thrust equation (see Section 9.1.).

$$T_{max} = (A \cdot c + A \cdot P \cdot \tan \phi + \Delta T') \cdot f(slip)$$

where:

A	=	track/ground contact area	$inches^2$
C	=	coefficient of cohesion of soil	psi
P	=	ground pressure	$lb/inches^2$
φ	=	angle of soil friction	degrees
$\Delta T'$	=	the additional shearing force produced by the grousers on the track	
f(slip)	=	monotonic function of slip in the following manner:	

a) Assumption 1 implies $A \cdot P \tan \phi >> A \cdot c$

b) Assumption 2 implies $F(slip) \simeq 0$

c) Assumption 3 implies $\Delta T' \simeq 0$ since $\Delta T' = 0.64 \left(\frac{h}{b} \cdot \text{arcctn} \frac{h}{b}\right)$

where:

h = grouser height = 0.89 inches
b = track width = 28 inches
(a T142 track is assumed (see Section 2.1), thereby,
$\Delta T' = 0.031$ lbs

and the soil thrust equation reduces to:

$$T_{max} = A \cdot P \cdot \tan \phi$$

When the tank is stationary and on level ground the above equation is equivalent to:

$$T_{max} = \mu_s \cdot W$$

Where μ_s = static coefficient of friction

W = vehicle weight ~ lbs

When the tank is moving on level ground, the reduced soil thrust equation is equivalent to:

$$T_{max} = \mu_k \cdot W$$

Where:

μ_k = kinetic coefficient of friction which is less than μ_s since the ground pressure decreases as velocity increases

As the above equation implies, the k variable μ_k could also be a function of track/ground contact area.

The other simplifying assumptions relate to motion resistances. The first assumption (sinkage is negligible ($Z \cong 0$) implies that compaction and bulldozing resistances are negligible, and therefore,

4) The total resistance to motion is comprised of two additional components: rolling resistance

$$R_r = f_o \cdot W$$

(where: f_o = coefficient of rolling resistance including such factors as aerodynamic resistance, mechanical friction in the track and final drive gear box, and track slip resistance).

and grade resistance

$$R_g = W \cdot \sin\theta$$

(where: θ = the inclination angle of the terrain).

The equations of motion are divided into translational and rotational equations of motion. Translational equations are computed with respect to a fixed, i.e., assumed inertial for the time duration of a specific training mission, axis system defined in the tactical area. Rotational equations of motion will be computed with respect to a body axis system. Since the tank is always in contact with the ground, the rotational equations of motion will be kinematically simulated with the dynamic characteristics superimposed using first order time lags. In particular, the steady-state attitude of the tank is defined by the visual data base beneath the tank. Therefore, dynamically assuming a first order time lag:

$$\dot{\theta} + k_1 (\theta_t - \theta_{t_{ss}}) = 0$$

where:

θ = pitch rate

θ_t = present pitch attitude of the tank
$\theta_{t_{ss}}$ = new pitch attitude of the tank

using the rectangular numerical integration:

$$\theta_t = \theta_t + \Delta T \cdot \dot{\theta}$$

and substituting:

$$\theta_{t_{i+1}} = \theta_{t_i} + \Delta T \cdot k \cdot (\theta_{t_{ss}} - \theta_{t_i})$$

Also, the rate of turn will be made a function of differential torque transmission, vehicle velocity, and separation of the tracks. The effect of the firing the main gun will also be considered in the equations of motion. Moreover, the format of the equations will be guided by the form in which the data is available.

Since the visual system is a DIG, rather than a camera/model system, information describing the soil/terrain beneath the tank can be supplied by the visual system. The following data is required for five fixed points attached to the vehicle per frame:

1) The distance from each of the five points to the ground parallel to the data base Z axis.

2) The vector normal to the face directly below each point.

3) An index indicating the surface materials of the face below each point. This index is to be used in a table providing the coefficients for static and kinetic friction and roughness factors.

The five points are: (1) the simulated center of gravity, (2 & 3) points attached to the right and left leading edges of the tracks and (4 & 5) points attached to the right and left trailing edge of the tracks. These five points are sufficient for kinematically simulating the rotational equations of motion. The iteration rates of the equations of motion will be the same as the visual system iteration rates.

Table 9-1 is a comparison of the approaches investigated and the chosen approach for FCIS. Also, Figure 9-2 is a generalized block diagram of the chosen approach.

TABLE 9-1 EQUATIONS OF MOTION COMPARISON

ITEMS	McKenzie	Perloff	Cook & Snowball	Link-Miles	Recommended for FCIS	COMMENTS
SOIL THRUST						
• Bekker's Equation	Yes	No	No	No	No	
• Perloff's Equation	No	Yes	NO	No	No	
• Static Friction	No	No	Yes	Yes	Yes	
• Kinetic Friction	No	No	No	No	Yes	Kinetic Friction = f(vehicle velocity)
• Slip	Yes	Yes	No	No	No	
MOTION RESISTANCES						
• Compaction Resistance	Yes	Yes	No	No	No	Perloff and McKenzie used different
• Bulldozing Resistance	Yes	Yes	No	No	No	" " " " equations
• Grade Resistance	Yes	Yes	Yes	Yes	Yes	
• Rolling Resistance	Yes	Yes	Yes	Yes	Yes	Perloff and McKenzie indirectly

TABLE 9-1 EQUATIONS OF MOTION COMPARISON (CONT'D)

ITEMS	McKenzie	Perloff	Cook & Snowball	Link-Miles	Recommended for FCIS	COMMENTS
TYPES OF SOIL						
• Predominantly Cohesive	Yes	Yes	No	No	No	
• Predominantly Friction	Yes	Yes	Yes	No	Yes	Link-Miles did not correlate friction with type of soil
• Cohesive, Friction Mix	Yes	Yes	No	No	No	
• Effect of Weapon Fire	No	No	No	No	Yes	
VISUAL SYSTEM INTERFACE	No	No	No	Yes	Yes	
CORRELATION TO VISUAL	No	No	No	No	Yes	FCIS Visual is a DIG
EFFECT OF WEAPON FIRE	No	No	No	No	Yes	

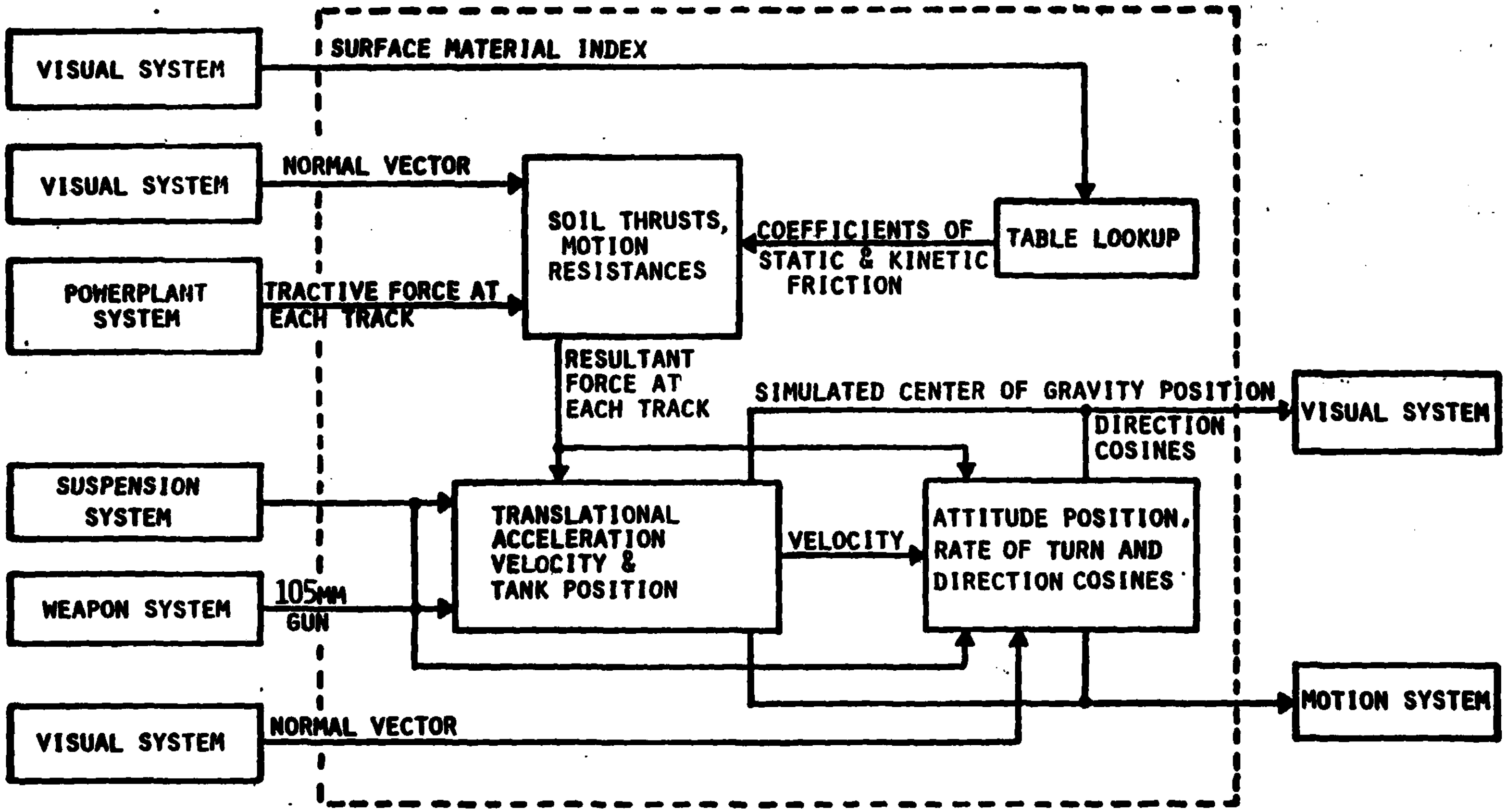

Figure 9-2 Equations of Motion - Generalized Block Diagram

9.1.2 Powerplant. Powerplant simulation should include the simulation of the engine, fuel controller, transmission (including the steering and braking sub-units), engine and transmission indicator and controls, and final drive.

F.B. Cook and W. Snowball and Roy D. McKenzie discussed powerplant simulations used in their respective engineering simulations. However, for a training application, simulation must include dynamic and steady-state response to accelerator and brake pedal deflection, steering commands, and transmission shift lever position. Therefore, the initial sequence of the approach must be and include:

1) Demanded RPM = A function of accelerator pedal position

2) Fuel flow = A function of the difference between demanded and actual RPM, and ambient air temperature and pressure effects - if any (note: this function includes the fuel governor function.)

3) The rate of change of RPM = A function of the difference between acceleration/deceleration fuel flow and steady-state fuel flow.

From this point, the approach of Cook and Snowball can be referenced. In particular, Cook and Snowball simulated the AVDS-1790-2A engine and CD-850-6A transmission power package, (an earlier model of the engine in the M60A3). The result must include the calculation of the tractive effort or the thrust available at the sprocket. For example:

$$T = \frac{2 \cdot T_t \cdot R_{fd} \cdot E_{fd}}{D_p}$$

where:

T_t = Transmission output torque
R_{fd} = Final drive reduction ratio
E_{fd} = Final drive efficiency
D_p = Pitch diameter of the drive sprocket

Powerplant simulation must include all phases of engine operation - including startup, running, and stopping under various weather conditions.

9.1.2.1 Powerplant Simulation. Powerplant simulation will include all the functions listed in 9.1.2.

Figure 9-3 is a generalized block diagram of the powerplant simulation approach. The chosen approach was derived by referencing the engineering simulations by Cook and Snowball, and McKenzie. McKenzie noted "..... that power

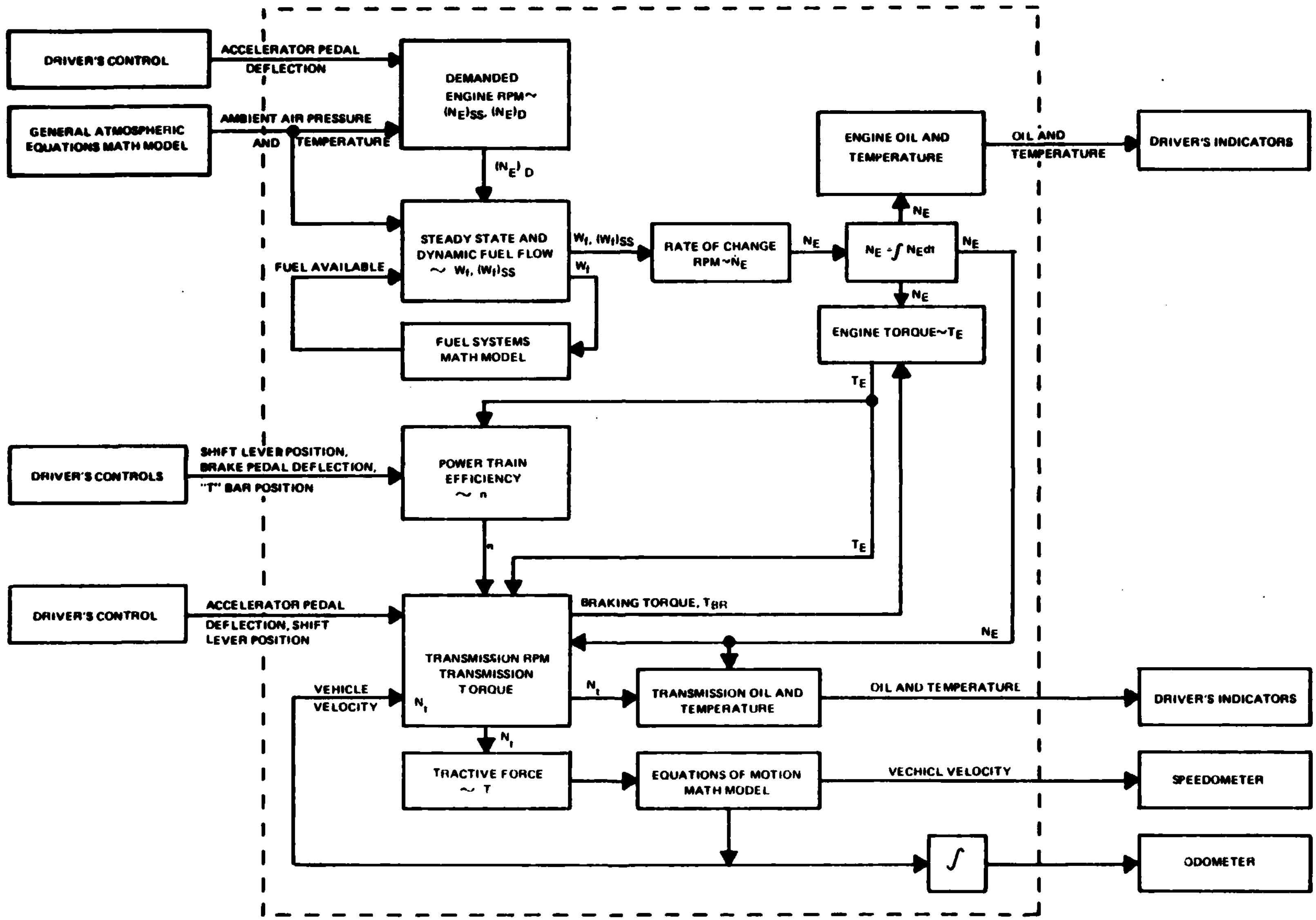

Figure 9-3 Powerplant - Generalized Block Diagram

losses due to atmospheric conditions can become substantial and should not be neglected."
and pressure are being considered in the approach at this time.

Both Cook and Snowball and KcKenzie, use the power train efficiency variable in their simulations. McKenzie generally describes the variable as:

> "The power losses,which result in the process of transmitting engine power to the driving wheels or sprockets,are due mainly to the clutch, transmission, differential, universal joints and bearings, and oil churning in the gear box. The magnitude of the total power loss between the engine and the drive axle is usually given as the power train efficiency η and is measured experimentally on a dynamometer. In general, η is found to depend upon gear reduction ratio, and to be higher for low reduction ratios."

Therefore, it is expected that power train efficiency is a function of engine torque, shift lever position, brake pedal deflection, and "T-bar" position. Then, the ratio of transmission output shaft speed to input shaft speed (N_t/NE) can be calculated as a function of the power train efficiency. By definition of the power train efficiency, the transmission power in horsepower is related to the engine power in horsepower as:

$$P_t = n \cdot P_E$$

$$\frac{2\,\Pi \cdot N_t \cdot T_t}{33{,}000} = \eta \cdot \frac{(2\,\Pi \cdot N_E \cdot T_E)}{33{,}000}$$

which implies that

$$T_t = \frac{\eta \cdot N_E \cdot T_E}{N_T}$$

where T_t is the transmission output torque.

At this time the tractive effort produced by the powerplant is:

$$T = \frac{2 \cdot T_t \cdot R_{fd} \cdot E_{fd}}{D_p}$$

Where:

R_{fd} = final drive reduction ratio
E_{fd} = final drive efficiency
D_p = pitch diameter of the drive sprocket

The braking torque logic is initiated when no accelerator pedal deflection exists. Then, braking torque is a function of vehicle velocity and shift lever position. If engine torque, at an idling speed, is greater than braking torque, then engine torque is limited to braking torque and the appropriate variable change as a function of the braking torque.

Data to support this approach must be supplied by the engine and transmission manufacturers. This is a reasonable assumption since the Cook and Snowball approach was based on a working engineering simulation of the similar M60A1 tank by Cook and Snowball.

Engine oil temperature will be simulated dynamically. Oil temperature rate of change will be computed using models for all heat sources and cooling mechanisms affecting oil temperature. Fuel consumed in the engine, thermal conversion efficiency of the consumption, and internal friction losses will be modeled as heat sources. The oil cooler will be modeled considering the temperature of the cooling air, the air flow of the engine driver fans, and engine speed. All models will be developed using detailed data on the design and efficiencies of the actual tank hardware. The actual oil temperature will then be computed by integrating the rate of change of oil temperature. This completely analogous simulation will provide the driver with the steady-state indications of engine operation, along with the transients and time histories peculiar to actual engine operation.

Transmission oil temperature will be simulated in a similar fashion. In this case, energy inputs are transmission losses. The additional restraint on cooler oil flow of the thermostat (185°F) operation will be incorporated. Engine oil pressure will be simulated as a function of oil temperature and engine speed; transmission oil pressure will be computed as a function of input and output speeds (corresponding to the two transmission oil pumps) and the transmission oil temperature.

9.1.3 Suspension System. As mentioned in Section 3.1.2, low operational speeds occur not only when the ground is soft and weak but when it is hard and strong as well. Vehicle speed must be radically reduced to minimize vibration. Vehicle response to ground roughness is dependent on its dynamic characteristics to allow safe operation and prevent mechanical failures.

Generally, there exist two approaches for simulation of the suspension system: 1,) individual roadwheel response to ground roughness, and 2,) overall vehicle response via transfer functions in each of the required degrees of freedom.

The approaches of Dale R. Bussman, Roy D. McKenzie, et al and F. Pradko et al are representative of the current state-of-the-art in roadwheel response simulation. Bussman assumed the vehicle to be moving at a constant velocity and developed vehicle response equations in three degrees of freedom; bounce, pitch and roll. M. G. Bekker discusses vehicle response using transfer functions. Transfer functions are functions of the velocity of the tracked vehicle. The actual response of the vehicle will be a function of the ground waves typical to the given terrain and the transfer function. The ground waves are the sinusoidal functions characteristic of the terrain beneath the tank (see Section 3.1.2).

Both approaches are acceptable depending on the purpose of the simulation. However, simulation of individual roadwheel response would be more accurate. The simulation of each of the twelve wheels for the M60A3 would involve spring-mass-damper systems for each roadwheel. This added complexity is not required by the driver to complete his task as discussed in Section 5,since the weight of the vehicle is approximately 50 tons, and thereby possesses a low natural frequency. In comparison, the Sheridan armored vehicle, being lighter than the M60A3, possesses a higher natural frequency and could require individual roadwheel simulation.

9.1.3.1 Terrain/Suspension System Interaction. Section 5.4 describes the FCIS training requirements for the driver. In a tactical situation, the tank driver must operate his vehicle over varying terrain and under a wide range of visibility conditions, trying to conceal the tank's passage while selecting advantageous firing positions as well as exit routes. The driver must learn to recognize many differences in the surface characteristics of the terrain, and to anticipate the effects of those characteristics on the tank's performance. As a result of terrain conditions, the limiting speed not always determined by the powerplant but by vehicle response to the terrain surface. The driver must consider what vibration levels can be tolerated by the crew and the tank itself.

These vibrations are induced by the interaction of the suspension system to the terrain; i.e. vehicle/terrain motion vibrations. In the chosen approach, vehicle response will be determined by using transfer functions. Transfer functions will be a function of the vehicle velocity. The actual response of the vehicle will be a function of the ground waves typical to the given terrain and the transfer function. The transfer functions are characteristic of the suspension system design of the M60A3. The suspension system consists of torsion bars attached to each roadwheel and shock absorbers attached to the front and rear roadwheels. The transfer function will be supplied by the tank manufacturers or by a test/evaluation center. It is anticipated that individual transfer functions will be required for bounce, pitch and roll.

The roughness factor of the terrain beneath the tank will be determined via a table using the surface material index supplied by the visual system for each of the five points attached to the vehicle (see Section 9.1.1). The output will be the bounce, pitch, and roll accelerations to the equations of motion in order to be summed with vehicle translational and rotational accelerations prior to their input to the motion system math models.

The roughness factor will consist of the amplitude and frequency that define the terrain. There will also exist, a random-number subroutine that will vary the amplitude, within the limits, and time duration of the amplitude. Moreover, there will be a control device on the instructor/operator station (IOS) that will vary the maximum/minimum amplitude limit.

Figure 9-4 is a generalized block diagram summarizing the chosen approach.

9.2 Motion Simulation

Motion simulation requirements were established in Section 7.2. It is the objective of this section to relate motion simulation requirements established in Section 7 to the system concepts formulated to satisfy them. A comparison of single vs. dual motion platform approaches is presented in 9.2.1. Dual platform approaches are discussed in Section 9.2.2. A discussion of methods to provide vibration cues to the crew is presented in 9.2.3.

9.2.1 Single Vs. Dual Motion System. The single platform approach has some distinct advantages over a dual platform approach. These are: lower facility costs, larger visual field-of-view, and lower motion system costs. This approach would also place the entire crew together at one crew station. There are also several disadvantages. Only those directly associated with motion simulation will be discussed herein. Those pertaining to other systems are discussed in their respective sections.

The disadvantages of a single motion system approach, from a motion simulation point of view, can be separated into two main categories - flexibility and cuing. Flexibility is an extremely important attribute if a simulator laboratory model is to be used to establish future simulation requirements; for either interactive or individual crew member training. The standard approach with this type of simulator (as employed on the U.S. Air Force's Advanced Simulator for Undergraduate Pilot Training (ASUPT), a simulator to establish requirements for basic jet training, is to provide the capability in the laboratory model to systematically degrade performance to establish the minimum training requirements.

For motion simulation, it is particularly important to be able to independently degrade degrees of freedom for the driver and for the occupants of the turret. This can only be accomplished by employing separate motion systems. There must be no contamination of results from one crew station to the other. Furthermore, the types of motion cuing necessary at each crew station

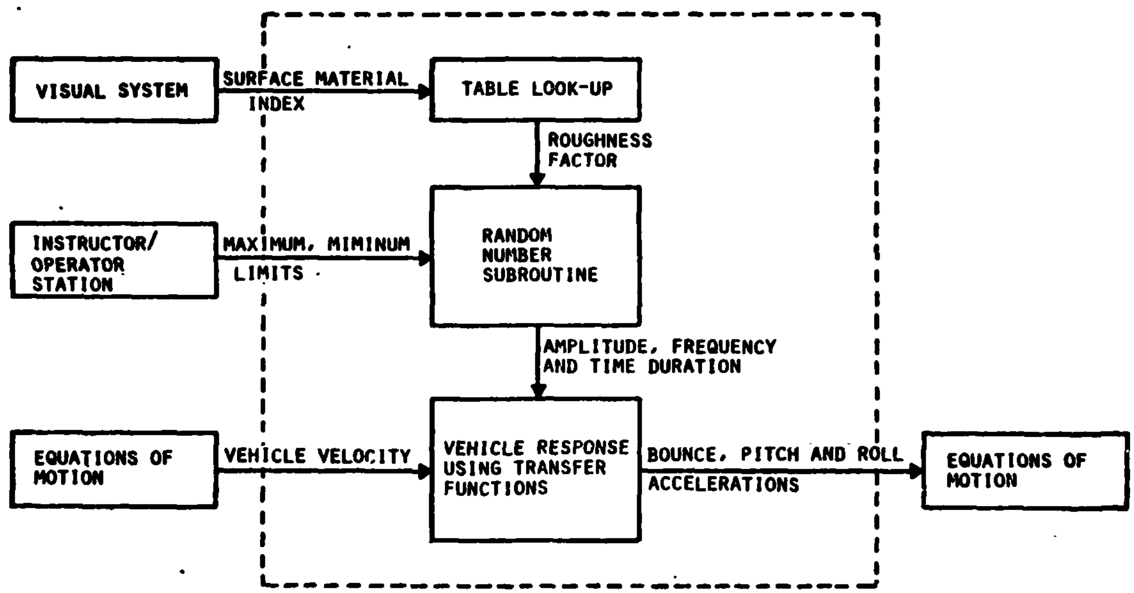

Figure 9-4 Suspension System - Generalized Block Diagram

may be more easily determined in an environment of separate motion systems.

Another advantage of the flexibility offered by the dual platform approach is that the devices may be used directly as a driver trainer and as a turret crew trainer. A major point is that separate research can be accomplished simultaneously in the two devices.

The area of cuing is where additional benefits may be realized by employing dual motion systems. As indicated in Section 7 (Volume II): If one motion base is used, the option of using onset cuing for turret rotation is forfeited and continuous turret rotation must be employed. Continuous turret rotation, means that the turret must have essentially the same rotational capability in the simulator as it does in the tank. Simply using 360 degrees of rotation is not adequate because of the reverse cue from reinitializing the turret. Using a continuously rotating turret introduces other problems such as video transmission through slip rings (discussed elsewhere).

In addition,the geometry of the tank; i.e., the driver's position relative to the turret crew must be maintained or false cues will be introduced on rotation. This precludes any possible foreshortening of the device to facilitate visual system implementation. Finally; the simulated turret would have to have the same structural characteristics as the tank to properly transmit cues between stations. The bases of these last two points are also discussed in Section 7.

It is felt that the lack of flexibility and the inability to provide adequate cuing at both stations, precludes the implementation of the single platform approach. It is further felt that the additional costs of attempting to ensure proper cuing will greatly reduce if not eliminate any training benefits.

9.2.2 Dual Platform Approaches. In this approach, two configurations were considered for the driver's station and three for the fighting station.

The first option for the driver station was a 4-degree-of-freedom system (pitch, roll, longitudinal and vertical); the second, a 6-degree-of-freedom motion system. The three options considered for the fighting station included: a 3-degree-of-freedom motion system (pitch, roll and longitudinal) with a continuously rotating turret cascaded on top of the platform, a 4-degree-of-freedom motion system (pitch, roll, longitudinal and lateral) with a turret rotation sufficient to provide onset cuing and cascaded on top of the platform, and a 6-degree-of-freedom motion system. Tradeoff analyses and rationale for the selection of one of these systems are located in 9.3.

9.2.3 Vibration Methods. There are three methods of providing vibratory cues to the various crew members. Before discussing these methods, some background information concerning vibratory cues is in order. Vibration is generally considered to be a continuous, periodic motion of either fixed or varying frequency and/or amplitude. Vibration, in this application, should not be confused with the "shudder" which might propagate through the vehicle as a decaying sinusoidal disturbance resulting from a shock.

Experience has shown that a vibration cue is not necessarily required in a specific degree of freedom. It seems that humans are more concerned with the frequency and amplitude or existence of the disturbance than with its direction. Therefore, two of the three methods of providing vibration cues involve only one degree of freedom.

The three methods to be discussed herein are:

- Seat shaker
- Crew station shaker
- Motion system

The seat shaker simply vibrates the crewman's seat; the crew station shaker vibrates the entire crew station; and the motion system option allows the presentation of vibration cues via the motion system hardware. With this option, vibration can possibly be introduced in any of the motion system's degrees of freedom.

All three methods have been successfully employed in flight simulators. Usually, seat shakers and cockpit shakers are employed when high-frequency vibration (3 Hz to 20 Hz) is required. Motion systems can provide up to 10 Hz vibration frequency. After analysis of the available data, it has been concluded that FCIS requirements do not warrant the addition of hardware beyond that presently available in the motion system. Significant vibrations occur at 5 Hz or below. Therefore, use of a standard motion system would be quite satisfactory. In addition, the motion system would provide the capability of introducing vibrations into the various degrees of freedom to ascertain training value.

Vibrating a motion system at higher frequencies reduces component life, may excite resonances, and requires considerable structural stiffening of components mounted on the platform.

9.3 Motion System Tradeoff Analysis and Selection

The rationale leading to the recommendation of dual platforms rather than a single platform was presented in 9.2.1. The options for the driver and the fighting station were described in 9.2.2.

Fighting station tradeoff analysis and system selection is presented in 9.3.1; driver's station in 9.3.2.

9.3.1 Tradeoff Analysis and Selection-Fighting Station. As previously stated, three options were analyzed to provide motion cues to the fighting station. Table 9-2 presents, in tabular form, the qualitative aspects of the tradeoff analysis.

The table is divided into two sections - "parameters" and "criteria". The first delinates the performance parameters and the second delineates all aspects of the tradeoff. Weighting factors were established in terms of relative importance. A weighing factor of 0.5 is the highest assigned.

The sub-categories under performance parameters were assigned weighting factors such that the summation was 0.5. System compatibility and safety were also assigned weighting factors of 0.5. But, for safety, all approaches met safety requirements equally so this item essentially has no overall impact. Effectivity factors (EF) are a measure of how well a particular approach satisfies a particular criterion. An effectivity factor of 5 implies maximum satisfaction of a criterion and values were assigned to other systems relative to that maximum.

The performance parameters considered to be most important were turret rotation cues and gunfire cues. For turret rotation cues, it was felt that all three systems could meet the requirements equally well. This is a statement of the fact that onset cuing with suitable washout provides satisfactory cuing. Gunfire cues are considered important because of the disturbance imposed on the turret crew. Terrain cues, maneuvering and acceleration cues and cue synchronization are of essentially equal importance.

The 6-degree-of-freedom motion system has the lowest procurement cost because the FCIS requirements are well within the capabilities of any one of several synergistic motion systems on the market presently. However the operating costs reverse the order as might be expected. Simplicity is considered to be of relatively low importance if reliability/maintainability and operating costs are good.

System compatibility is a measure of how well the option meets overall system requirements. Producibility/availability is self explanatory and the EF assigned each option indicates that the 6-degree-of-freedom system is an "off the shelf" item whereas the others must be designed or extensive modifications of existing systems must occur.

TABLE 9-2 TRADEOFF ANALYSIS/SELECTION CHART. SYSTEM: MOTION; SUBSYSTEM: FIGHTING STATION

	TRADE-OFF PARAMETERS AND SELECTION CRITERIA	WEIGHTING FACTOR	3 DOF PLUS CONTIN-UOUS TURRET ROTATION		4 DOF PLUS LIMITED TURRET ROTATION		6 DOF INCLUDING LIMITED TURRET ROTATION					
	PERFORMANCE PARAMETERS		EF	FM	EF	FM	EF	FM	EF	FM	EF	FM
PARAMETERS	• TERRAIN CUES	0.09	3	.27	4	0.36	5	.45				
	• MANEUVERING & ACCEL. CUES	0.08	4	.32	5	0.40	5	.40				
	• TURRET ROTATION CUES	0.15	5	.75	5	0.75	5	.75				
	• GUNFIRE CUES	0.10	2	.20	3	0.30	5	.50				
	• CUE SYNCHRONIZATION	0.08	3	.24	4	0.32	5	.40				
	PERFORMANCE SUMMATION			1.78		2.13		2.50				
CRITERIA	OVERALL PERFORMANCE			1.78		2.13		2.50				
	LOW PROCUREMENT COST	0.3	4	1.2	3	0.9	5	1.5				
	LOW OPERATING COST	0.4	5	2.0	4	1.6	3	1.2				
	SIMPLICITY	0.2	4	0.8	3	0.6	4	0.8				
	RELIABILITY	0.25	5	1.25	3	0.75	4	1.0				
	MAINTAINABILITY	0.25	5	1.25	4	1.0	3	0.75				
	SYSTEM COMPATABILITY	0.50	3	1.5	4	2.0	5	2.50				
	SYSTEM FLEXIBILITY	0.40	2	0.8	3	1.2	5	2.00				
	PRODUCIBILITY/AVAILABILITY	0.40	2	0.8	1	0.4	5	2.0				
	SAFETY ASPECTS	0.50	5	2.5	5	2.5	5	2.5				
	OVERALL SUMMATION		13.88		13.08		16.75					
	APPROACH REJECTION/SELECTION		X		X		✓					

The figure of merit (FM) is the product of weighting factor and effectivity factor and the sum of all figures of merit indicate the overall ranking of each option.

The result of this analysis indicates a clear superiority of the 6-degree-of-freedom system over the other options. This result is largely a function of its performance, system capability and availability and flexibility.

9.3.2 Trade-off Analysis and Selection-Driver's Station. Two options were analyzed to provide motion cues to the driver's station. These two options are a 4-degree-of-freedom system providing pitch, roll, longitudinal and vertical capability, and a 6-degree-of-freedom motion system.

Table 9-3 presents the results of the driver station motion tradeoff analysis. The table is similar to that one used for the fighting station, with slightly different emphasis. At this station, terrain and acceleration cues are considered to be the most significant becuase they provide the most significant information used when in driving the tank. Next, in order of significance, are maneuvering cues. These cues are those which result from turning. The 4-degree-of-freedom system does not perform as well here due to the lack of yaw or lateral capability. However, some cuing is available from slowing down and perhaps from slight rolling motions. As the tradeoff analysis illustrates, the minor variations in the total figures of merit between the two systems does not yield a clear cut advantage to the 6-degree-of-freedom system. Slight changes in some effectivity factors could reverse the outcome. However, since there is a clear advantage to the 6-degree-of-freedom system in the case of the fighting station, there would be some good reasons to select it for the driver's station even if the tradeoff analysis indicated the selection of the 4-degree-of-freedom system. One reason would be the added flexibility available with the large system (for experimentation in the laboratory environment). The second advantage would be in terms of commonality; spare parts inventories would be smaller, training of maintenance personnel would be less, interchangability of parts would be possible. These two factors are not totally reflected in the tradeoff analyses.

One other factor that should be considered is that the incremental difference in cost between a 4-degree-of-freedom motion system and a 6-degree-of-freedom system is extremely small when compared to the total cost of the device (less than 1%). Therefore it is felt that there is a substantial basis for recommending two 6-degree-of-freedom motion systems to satisfy the requirements of the FCIS.

TABLE 9-3 TRADEOFF ANALYSIS/SELECTION CHART. SYSTEM: MOTION; SUBSYSTEM SUBSYSTEM: DRIVER'S STATION

	TRADE-OFF PARAMETERS AND SELECTION CRITERIA	WEIGHTING FACTOR	4 DOF PITCH ROLL LONGITUDINAL VERTICAL		6 DOF							
			EF	FM	EF	FM	EF	FM	EF	FM	EF	FM
PARAMETERS	PERFORMANCE PARAMETERS											
	• TERRAIN CUES	.15	5	0.75	5	0.75						
	• MANEUVERING CUES	.10	2	0.20	5	0.50						
	• ACCELERATION CUES	.15	4	0.60	5	0.75						
	• GUN FIRE CUES	.02	3	0.06	5	0.10						
	• CUE SYNCHRONIZATION	.08	3	0.24	5	0.40						
	PERFORMANCE SUMMATION			1.85		2.50						
CRITERIA	OVERALL PERFORMANCE			1.85		2.50						
	LOW PROCUREMENT COST	0.30	5	1.50	3	0.90						
	LOW OPERATING COST	0.40	5	2.00	3	1.20						
	SIMPLICITY	0.20	5	1.00	3	0.60						
	RELIABILITY	0.25	5	1.25	3	0.75						
	MAINTAINABILITY	0.25	5	1.25	3	0.75						
	SYSTEM COMPATABILITY	0.50	3	1.50	5	2.50						
	SYSTEM FLEXIBILITY	0.40	3	1.20	5	2.00						
	PRODUCIBILITY/AVAILABILITY	0.40	2	0.80	5	2.00						
	SAFETY ASPECTS	0.50	5	2.50	5	2.50						
	OVERALL SUMMATION		14.85		15.7							
	APPROACH REJECTION/SELECTION		X		✓							

9.4 Development of Selected System

Since a 6-degree-of-freedom system has been recommended for each crew station; and the performance requirements in each degree of freedom are similar for each station; and because of the commonality argument presented in the previous section, the same system will be developed and employed at both crew stations.

Two types of 6 degree-of-freedom motion systems could be developed to satisfy the requirements of section 7.2.3 - a cascaded motion system or a synergistic system. A cascaded system (Figure 9-5) is one in which the excursion in any one degree of freedom is independent of excrusions in any other. A synergistic system may be characterized as (Figure 9-6) one in which motion in any degree of freedom degrades the instantaneous capability in all other degrees of freedom. This, however, is the only advantage of a cascaded system. It tends to be heavier, more expensive, and have servo loop stability problems. Synergistic systems, on the other hand, do not have those problems and offer the additional advantages of simplicity, ease of maintenance, superior performance, and greater flexibility.

In consideration of the aforementioned advantages and disadvantages, a synergistic 6 degree-of-freedom system is recommended.

9.4.1 Hardware Configuration. The system should have the capability of providing cues consistent with data originally presented in Table 7-3 (Volume II) and herein presented in Table 9-4.

In the 3 translational degrees of freedom (longitudinal, lateral and vertical), values for displacement, velocity, and excursion are the result of the application of onset cuing with second-order shaping to a "commanded position proportional to vehicle acceleration" philosophy. The motion system should have this capability to effect the appropriate cues. The yaw axis for the fighting station should employ onset cuing with "commanded angle proportional to turret rotational rate." The resulting characteristics are tabulated in Table 9-4. The value of 6.12 rad/sec^2 for yaw imposes ratner severe constraints and is somewhat unrealistic since it is a result of applying a maximum turret velocity step (0.39 rad/sec) in one iteration. Recorded data revelas that it would actually take about 3 computer cycles before the turret reaches maximum velocity. Re-analyzing on this basis, the required acceleration would be +2.0 rad/sec^2. This level is more reasonable and is a result of a unity ratio between platform and turret as well as relatively high poles in the cue shaper function. The cue shaper is discussed in 9.4.2. Hence, the acceleration requirements could quite readily be reduced further but it would be advantageous to have the additional capability for laboratory experimentation.

TABLE 9-4 MOTION EXCURSIONS AND ACCELERATIONS

Degree of Freedom	Mode	MOTION REQUIREMENTS: HULL Required	HULL Useful	TURRET Required	TURRET Useful
PITCH	DISP. VEL. ACC.	±0.64 rad ±1.11 rad/sec ±17.3 rad/sec^2	-	±0.64 rad ±1.11 rad/sec ±17.3 rad/sec^2	-
ROLL	DISP. VEL. ACC.	±0.3 rad ±0.52 rad/sec ±8.11 rad/sec	-	±0.3 rad ±0.52 rad/sec ±8.11 rad/sec^2	-
YAW	DISP. VEL. ACC.	- - -	- - -	±0.23 rad ±0.39 rad/sec ±6.12 rad/sec^2	-
LONGITUDINAL	DISP. VEL. ACC.	±10 in ±15 in/sec ±0.6g	-	±10.0 in ±15 in/sec ±0.6g	-
LATERAL	DISP. VEL. ACC.	-	±10 in ±15 in/sec ±0.6g	±10.0 in ±15 in/sec ±0.6g	-
VERTICAL	DISP. VEL. ACC.	±15 in ±25 in/sec ±1.0g	-	±15 in ±25 in/sec ±1.0g	-
VIBRATION	FREQ. AMPLITUDE	30 HZ 0.03g	-	5HZ 15 HZ 1.0g 0.05g	-

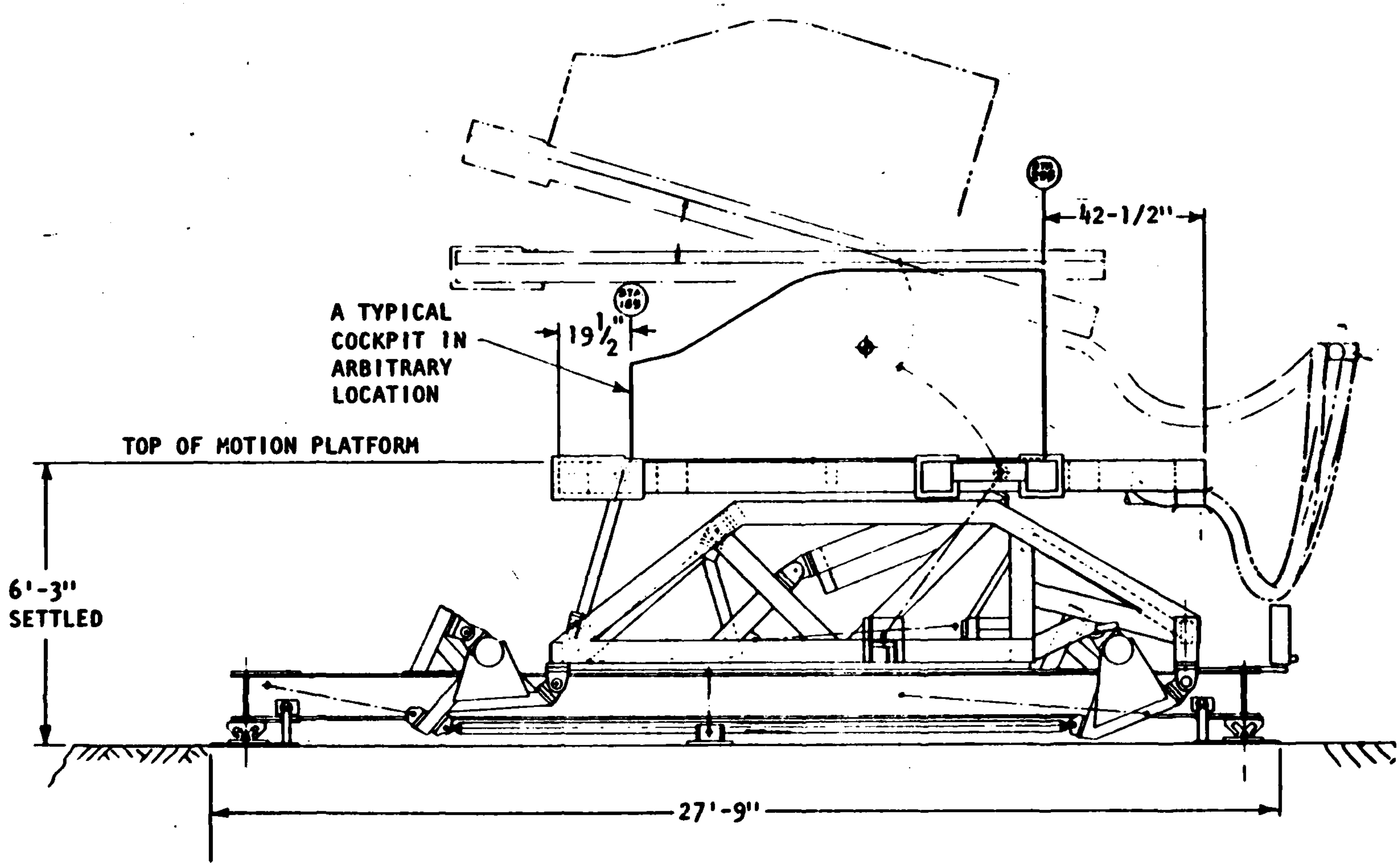

Figure 9-5 Cascaded 4 Degree-of-Freedom Motion System

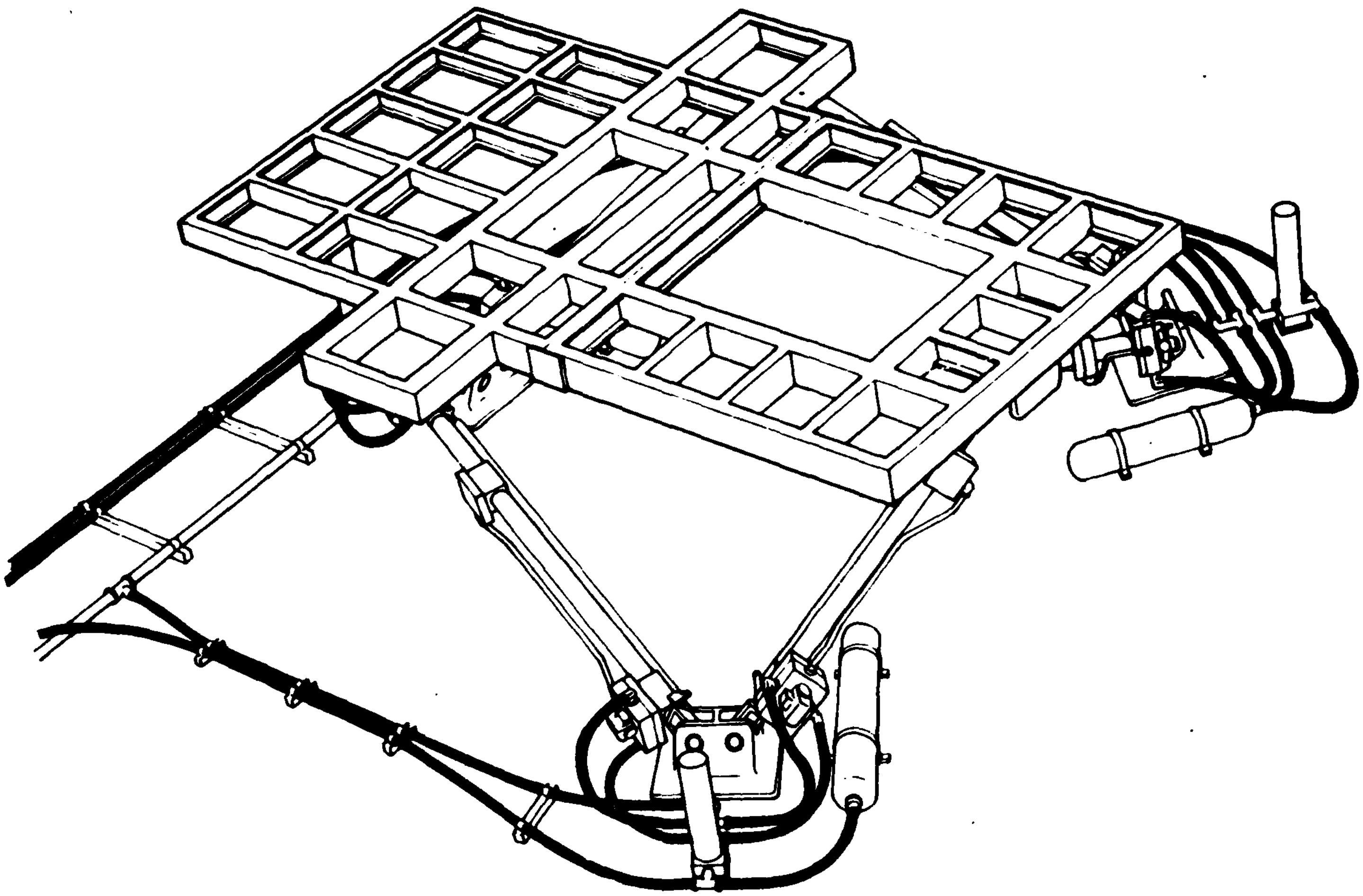

Figure 9-6 Synergistic 6 Degree-of-Freedom Motion System

The pitch and roll requirements for the ideal case; i.e. a one-to-one relationship between platform angle and tank angle, impose performance capabilities in excess of virtually all state-of-the-art motion systems. This same situation confronts the designer in aircraft simulation where an airplane can pitch to 90° and the simulator obviously cannot. Therefore, the ratio of pitch (or roll) angle of the platform to the corresponding angle of the aircraft is less than unity. This approach works quite well and if necessary can be augmented by adding onset cuing to initiate rotation. This augmentation does not appear to be necessary since the tank is not able to pitch or roll very rapidly unless it is falling. In this instance, the cue terminates quite rapidly so a mere saturation of the system would be sufficient. Therefore, the maximum capability in pitch and roll should be no greater than that required for fighter and transport aircraft. Those parameters are: excursion 50° total in pitch and ±20° in roll, a velocity of 17.5 deg/sec for pitch and 20°/sec for roll, and accelerations of ±60 deg/sec^2.

The recommended requirements for the 6 degrees of freedom are provided in Table 9-5.

TABLE 9-5 DEGREE OF FREEDOM REQUIREMENTS

DEGREE OF FREEDOM	DISPL	VEL	ACCEL.
YAW	±13°	±20°/sec	±114°/sec^2
PITCH	50° TOTAL	±17.5°/sec	±60°/sec^2
ROLL	±20°	±20°/sec	±60°/sec^2
VERTICAL	±15"	±25 in/sec	±1.0g
LONGITUDINAL	±10"	±15 in/sec	±0.6g
LATERAL	±10"	±15 in/sec	±0.6g

The motion system is mounted on a 36-inch vertical pedestal to allow sufficient clearance for the display hardware in worst case attitudes. Figure 9-7 and figure 9-8 illustrate the configurations for the fighting station and driver's station respectively.

The design of both stations is on Link's standard 6 degree-of-freedom motion system with the exception of the pedestal and a modified platform to interface with the visual display structures.

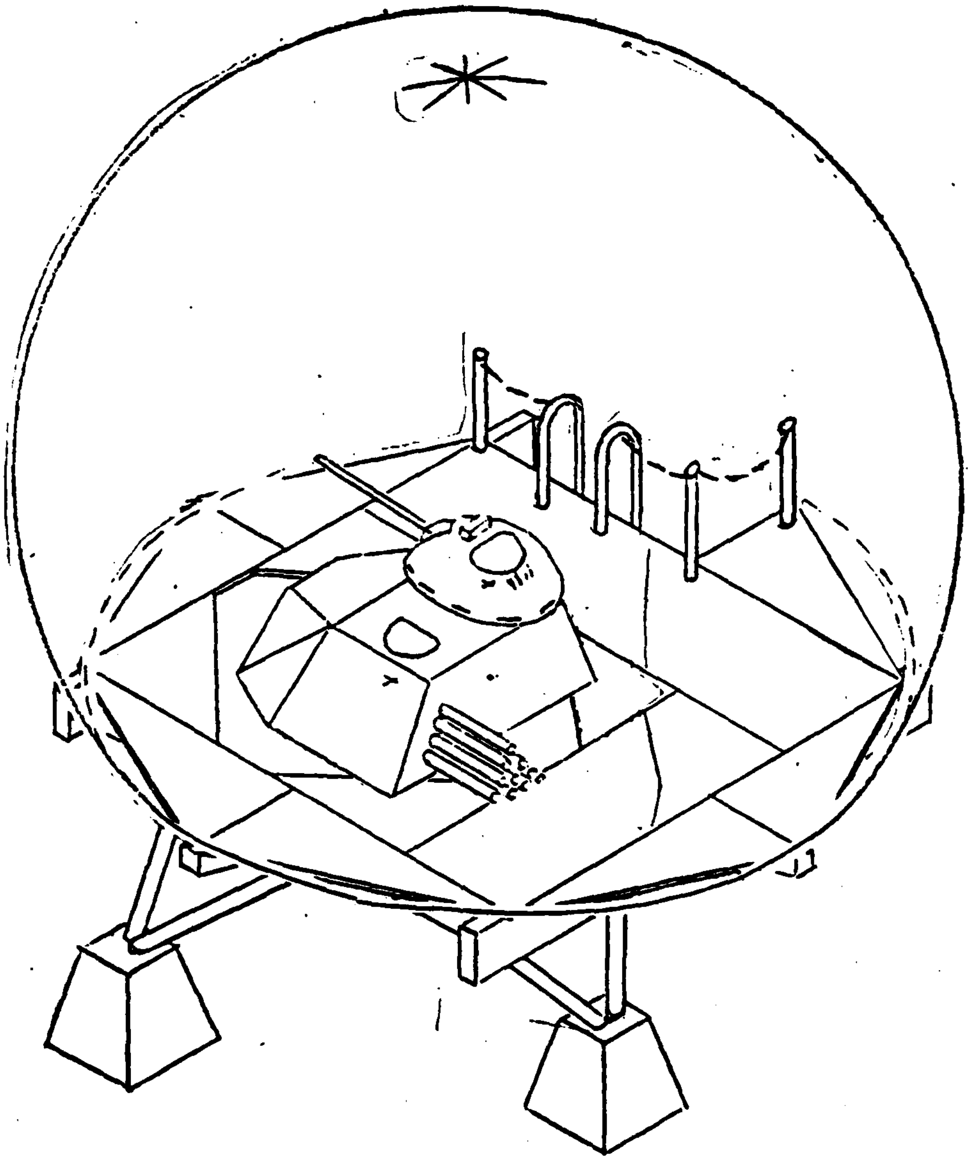

Figure 9-7 Fighting Station Motion Platform/Dome Arrangement

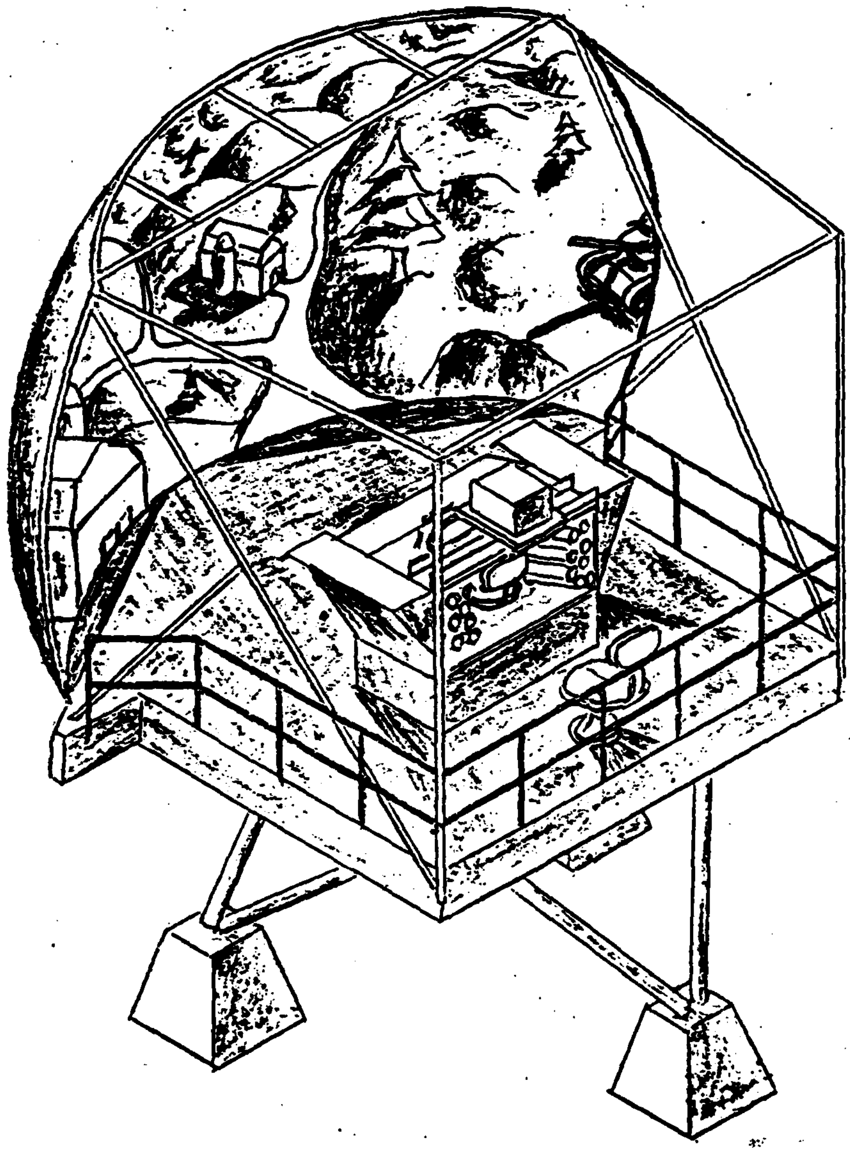

Figure 9-8 Driver Station Motion Platform/Screen Arrangement

Since a military standard exists for 6 degree-of-freedom motion systems (Mil-Std-1558 which is included as an attachment to Volume IV), and in most cases, FCIS requirements are similar, it is suggested that this standard be employed with the following exceptions:

a. 4.2.5 Velocity Requirements - PITCH 17.5^{o}/sec

b. 4.2.6 Acceleration Requirements - YAW 114^{o}/sec^{2}

c. 4.2.8 Damping - 2% overshoot

d. 4.4.2.1 Abrupt Motion - 0.70g

Modifications (a) (c) & (d) are currently being considered from Mil-Std-1558 by the cognizant agency, and since they do not jeopordize the performance of FCIS, are being suggested for inclusion here. Modification (b) is an increase in performance above Mil-Std-1558 and is suggested to meet the FCIS requirements.

9.4.2 Software Configuration. It is the objective of this section to describe the software required to drive the hardware in a manner to meet the requirements of section 7.2.

Figure 9-9 is a functional block diagram of the software system. The organization for both driver's station and fighting station software modules should be similar to take maximum advantage of the use of subroutines.

It is conceived that in order to provide experimental flexibility, the program structure should include several interchangeable subroutines. One general module should reside in the computer and should be indexed for driver's station motion or fighting station motion.

The dashed blocks in figure 9-9 provide compensation for turret angle and are included only in the fighting station program.

A discussion of the software required to implement the drive concepts follows and it is suggested that figure 9-9 be used for reference purpose.

Vehicle dynamics simulation provides required information concerning the vehicle orientation, velocity, and acceleration to the motion module. This information is then processed to compute the actuator commands to properly position the motion platform.

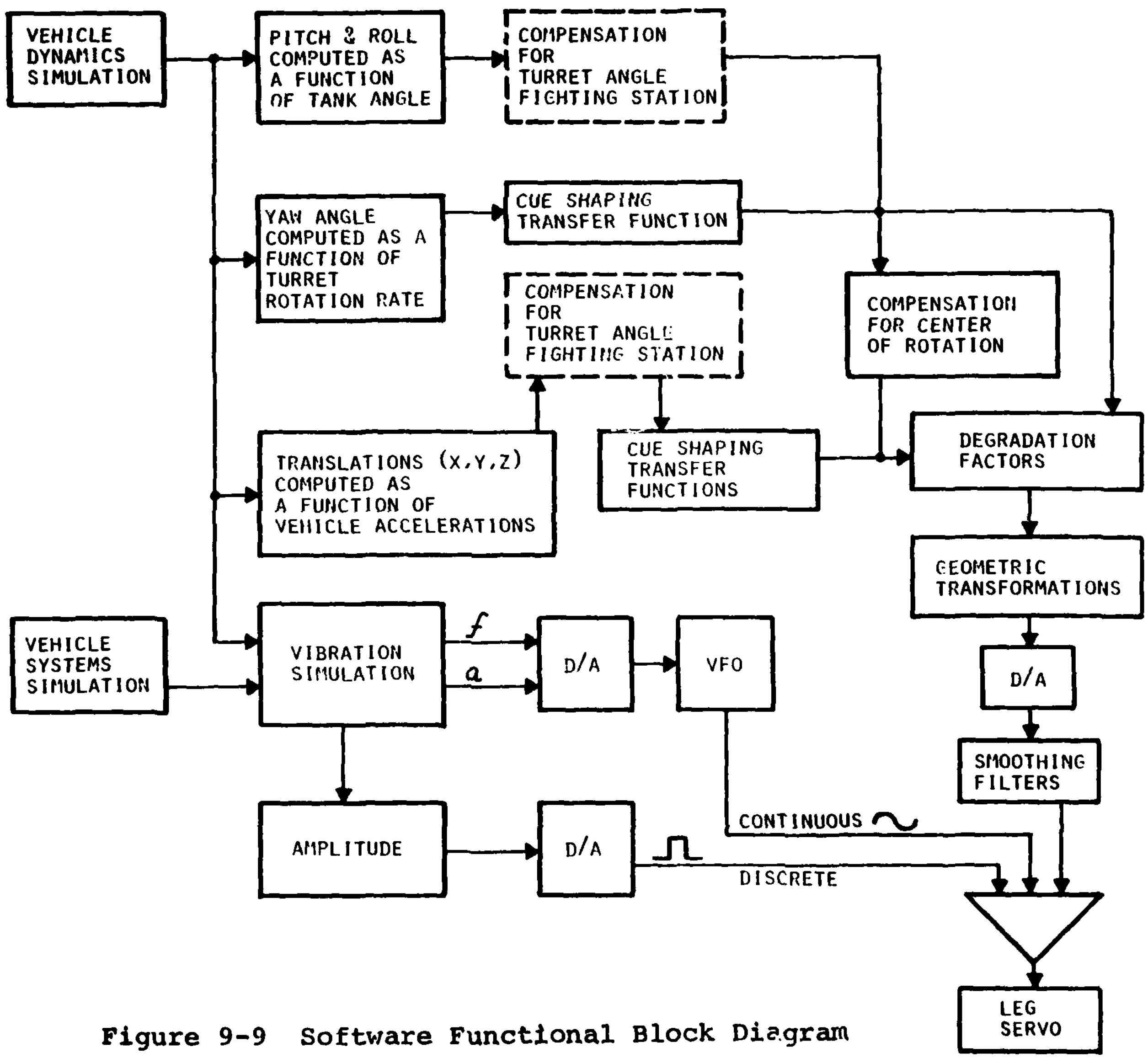

Figure 9-9 Software Functional Block Diagram

Platform pitch and roll will be kinematically computed by equations of the form

$$\theta_P = K_\theta \, \theta_T$$

$$\phi_P = K_\phi \, \phi_T$$

where θ_P and ϕ_P are the desired platform pitch and roll angles respectively, K_θ and K_ϕ are constants of proportionality and θ_T and ϕ_T are the pitch and roll angles of the tank. The two constants of proportionality should be easily variable by the experimenter in order to determine the crewmembers' sensitivity to the proportion of the real-world angle being produced in the simulator.

At the fighting station, compensation for turret pointing angle must be provided. For example; when the tank is proceeding with the turret pointing 90^o to the right, what is perceived as pitch in the hull is roll at the fighting station and vice versa.

The governing equations are of the form

$$\theta_P = \theta_T \cos \alpha_T + \phi_T \sin \alpha_T$$

$$\phi_P = \phi_T \cos \alpha_T + \theta_T \sin \alpha_T$$

where α_T is the pointing angle of the turret.

To provide onset cues for turret rotation, the position drive command should be a function of turret rotation rate. The drive equation should be

$$\psi_P = K_\psi \, \dot{\alpha}_T$$

where $\dot{\alpha}_T$ is the turret rotation rate.

This drive signal is then passed through a cue shaping, second order transfer function such as

$$G(S) = \frac{1}{(s+a)(s+b)}$$

where a and b are the poles which are under the control of the experimenter. The above transfer function is represented in the Laplace domain and must be expressed in the time domain for mechanization in the digital computer. The poles of this transfer function can be manipulated to control the slope of the onset cue and the shape of the washout profile.

The translational axes drive equations should all be a function of vehicle acceleration. These equations;

$$X_P = K_X \ddot{X}_T$$

$$Y_P = K_Y \ddot{Y}_T$$

$$Z_P = K_Z \ddot{Z}_T$$

are then used as drive parameters for the cue shaping functions which are of the same form as the yaw axis (although the poles may be different).

Next, a compensatory term should be added in the vertical and lateral directions, to establish the appropriate center of rotation. This additional term is a function of the distance to the center of rotation and the tank rotation angle.

The next set of computations provided, should enable the experimenter to degrade capabilities in any degree of freedom proportionately to zero; if, for example, the experimenter desires to validate the training effectiveness of cue in any degree of freedom.

An example of how degradation factors could be employed is shown here for the pitch axis:

$$\theta_{P_O} = K_{\theta_D} \theta_P$$

Therefore, if $K_{\theta_D} = 1$, the full effect of cues in the pitch axis are experienced. If $K_{\theta_D} = 0$, no cues in the pitch axis are provided. Also, cues may be partially reduced by inserting $0 < K_{\theta_D} < 1$. At this point the desired orientation has been computed and the individual ram commands must be computed. These are commands derived by employing a set of geometric transformation equations which relate platform position to leg commands. These six ram position commands are then converted from digital to analog signals and passed through a 3.3 Hz iteration rate smoothing filter.

A separate branch of the motion program as shown in figure 9-9 should b These include vibratory or any discrete special effects. These include vibratory or any discrete pulse cues. Vibratory cues are computed for any periodic type phenomena such as engine or road vibration. Discrete cues might arise from weapon strikes or collisions. The advantage of using this channel to provide these pulses is that it is unfiltered. The vibration drive equations may be configured to provide engine vibration as a function of engine RPM. Two drive signals; frequency and amplitude are required. They may be of the form

$$f = K_f(RPM)$$

$$a = K_a(RPM)$$

where f is the commanded frequency and a is the commanded amplitude. These signals control the output of a variable frequency oscillator which is summed with the leg commands from the primary cues section and the discrete channel.

9.4.3 Systems Integration and Synchronization. The synchronization of cues is critical to the successful perception of the simulated environment (Refer to Section 7).

In designing an FCIS, it is possible through the dedication of groups of experts in various disciplines, to arrive at a number of ideal systems that would satisfy all the individual systems requirements but are completely incompatible as an overall training device. The Link approach has been to utilize all the expertise available to develop concepts which are systematically subjected to the scrutiny of experts in all design areas at appropriately scheduled design reviews. Through this medium, all FCIS systems design recommendations have been traded against overall FCIS requirements as well as particular systems performance criteria.

When referring to the master decision tree, (Volume I) it is evident that certain critical design decisions were arrived at via this process. For instance: from a purely configuration design or motion system design aspect, the optimum design would not be a multi-station training facility. However, when considering the problem of satisfying visual systems requirements to provide realistic visual cues to both the driver and the tank commander simultaneously with one set of projectors on a single dome, the parallax error due to the physical separation of the two eye points makes the single training capsule with all simulated crew stations on a single motion system a very impractical solution. By separating the crew stations, the parallax problem may be obviated and at the same time, other difficult design problems, such as motion system loading, turret rotation, and transfer of turret signals, become more easily solvable. By separating the FCIS into a driver's station mounted on its motion system and the fighting station mounted on a completely separate motion system, it became feasible to simulate the turret rotation by contra-rotation of the visual scene and simulated hull. This allows realistic simulation of unlimited turret rotation with no requirement for unreliable slip rings to transfer electrical/video signals to and from the rotating turret.

Thus, throughout the study, there are numerous instances where the systems tradeoffs and resultant designs are the results of intra-system impacts which assure a fully integrated FCIS design.

The most critical aspect of cue synchronization is the correlation of the visual and motion systems. Figure 9-10 identifies hardware and software elements which should be considered in terms of their effect on the dynamic response of both systems. Also to be included, are the instrument drive systems. Instrument synchronization is less of a problem than in aircraft simulation since there are no navigational or high-response attitude instruments - only a tachometer and speedomter. Control inputs are used to compute vehicle dynamics. These parameters are then used to update the visual display through the visual system image generator and the motion system through the motion drive equations. Motion commands are converted to analog signals to drive the motion servo systems.

Each transfer of data and computation is additive to the delay from the time of input to the time of motion or visual response. If individual steps are not organized, controlled, and properly executed, resultant delays could become unacceptable (from the crewmembers' viewpoint).

One tool which may be used in satisfying cue synchronization requirements is a timing chart analysis. An example of a timing chart is shown in Figure 9-11 . This device is used to determine proper sequencing of programs to minimize time delays.

Through the use of this chart, worst case, best case, and average case time delays may be determined. The arrows at A and B represent control inputs at those two points - one just before I/O transfer and one just after. The reactions of the various systems are shown as arrows at the bottom of the lines. This chart does not necessarily represent the FCIS but is representative of the technique. Once the initial computer configuration is established the following techniques can be used to synchronize cues.

a. Iteration rate selection.

b. Sequencing of software modules.

c. I/O card servicing sequence

d. Special message update.

e. Software lead/lag functions.

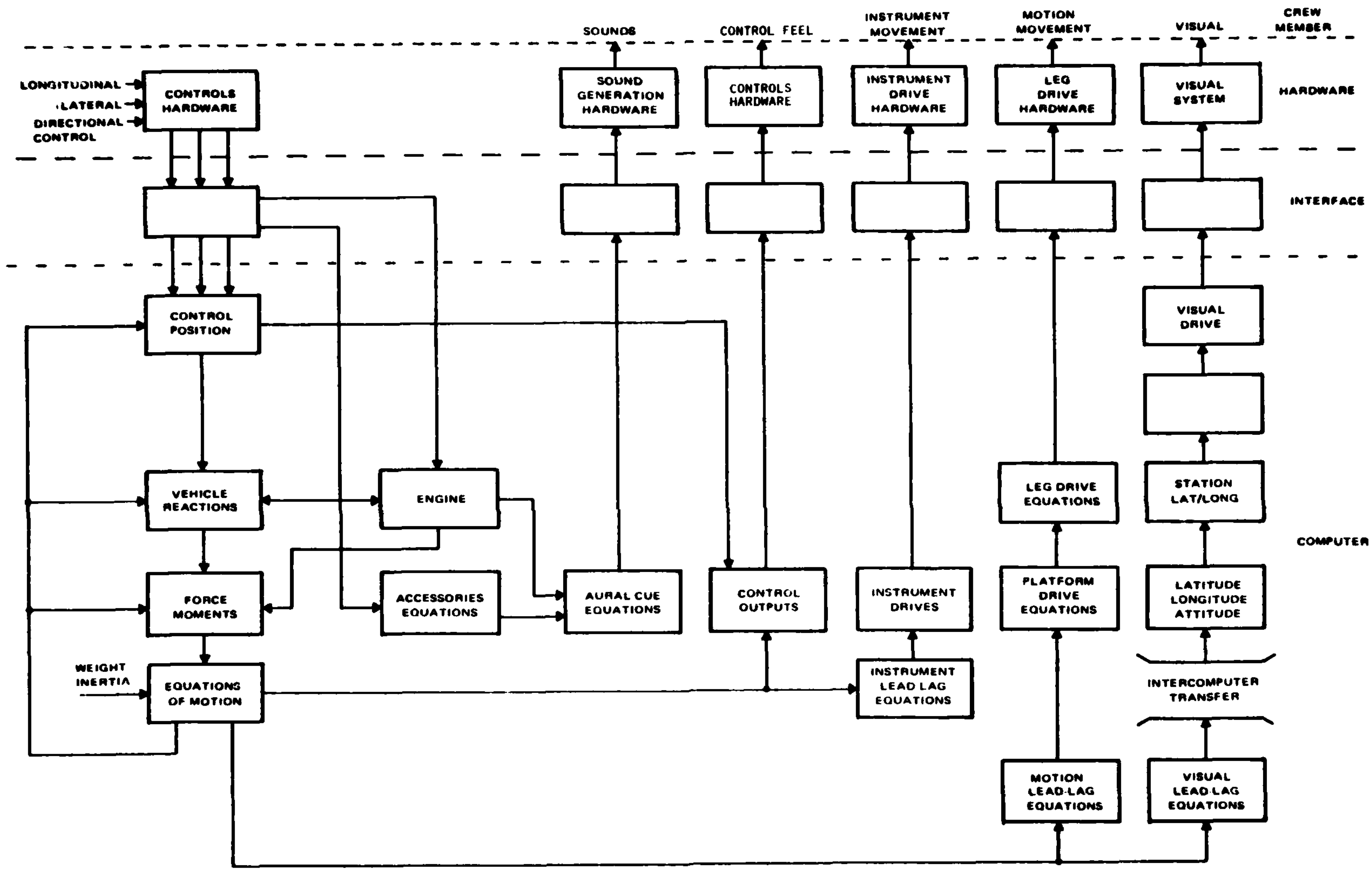

Figure 9-10 Typical Flow of Events From Input to Sensory Cue Output

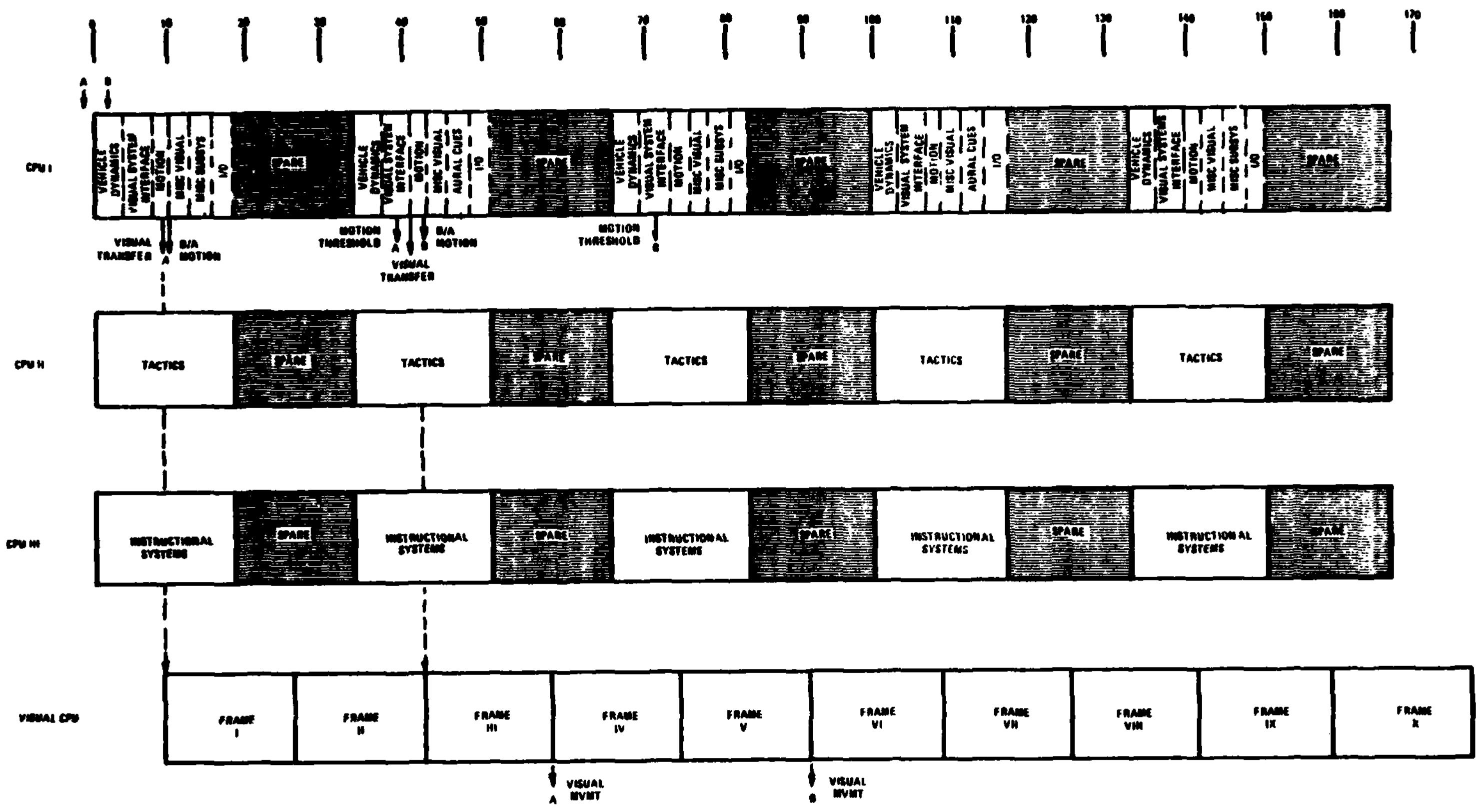

Figure 9-11 Timing/Sequencing Diagram

Techniques a, b and c are self explanatory. Special message update (d) involves transfering information in or out of the computer at a rate greater than the maximum update rate. Software lead/lag functions (e) are used to either lead or lag the output parameters. As applied to the motion parameters, this could take the form of a single interval lead;

$$\dot{\theta}_\ell = \dot{\theta}_T = \tau\ddot{\theta}_T$$

where τ is the lead/lag interval. If τ is positive, the function provides a lead of up to one quadrature interval. If τ is negative the function defines a lag. These lead/lag functions can be applied to any subsystem to assist in correlating cues.

9.5 System Flexibility

As indicated throughout this report, the system flexibility is considered to be of significant importance. Increased flexibility provides the experimenter with a wider latitude for verifying simulation requirements which optimize transfer of training. The purpose of this section is to consolidate all previous discussion of motion system flexibility.

A major step in the achievement of system flexibility is the 6 degree-of-freedom motion system. The utilization of the 6 degree-of-freedom system permits experimental determination of how many degrees of freedom are actually required.

Software configuration also contributes to overall motion system flexibility. Software formulations permit module interchangeability, ease of modification of drive signal philosophy, alteration of motion control low gains (constants of proportionality; e.g. K_θ), poles, and washout profiles. Degradation of overall motion performance and degrees of freedom add additional flexibility.

Based on the lack of experimental data relative to the effectiveness of training associated with parameters established for armor training devices, it has been considered that the laboratory model should provide the means of making this determination prior to the commitment to procure armor training devices - specifically - production model Full Crew Interactive Simulators.

ATTACHMENT 1

MIL-STD-1558

MIL-STD-1558
22 February 1974

MILITARY STANDARD

SIX-DEGREE-OF-FREEDOM MOTION SYSTEM REQUIREMENTS FOR AIRCREWMEMBER TRAINING SIMULATORS

FSC 6930

Attachment-1

MIL-STD-1558
22 February 1974

DEPARTMENT OF DEFENSE

Washington, D. C. 20360

Six-Degree-of-Freedom Motion System Requirements for Aircrewmember Training Simulators

MIL-STD-1558

1. This Military Standard is approved for use by all Departments and Agencies of the Department of Defense

2. Receommended corrections, additions, or deletions should be addressed to 4950/TZSS, Wright-Patterson Air Force Base, Ohio 45433.

Attachment-2

CONTENTS

CONTENTS (Cont)

TABLES

1. SCOPE

1.1 This standard covers the engineering requirements for six degree-of-freedom motion systems used in real-time aircrewmember training simulators and interface requirements between the motion system and other simulator subsystems. It is intended to be used as an aid in writing motion system requirements for use in detailed simulator specifications.

2. APPLICABLE DOCUMENTS

2.1 The following documents of the issue in effect on date of invitation for bid or request for proposal, form a part of this specification to the extent specified herein.

SPECIFICATIONS

Military

MIL-H-5606	Hydraulic Fluid, Petroleum Base; Aircraft, Missile, and Ordnance

STANDARDS

MIL-STD-1472	Human Engineering Design Criteria for Military Systems, Equipment and Facilities

(Copies of specifications, standards, drawings, and publications required by suppliers in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.)

3. DEFINITIONS

3.1 The following definitions are used herein:

a. On-off-Activation or deactivation of a pump.

b. Engage-disengage- Control of hydraulic fluid flow to the motion system.

c. Shut down - Deactivation of the entire hydraulic system.

d. Motion system pump(s) - The pump(s) which operate the motion system and which may operate the control loading system.

e. Control loading pump - The pump which operates the control loading system only.

f. Pump - Any pump from d or e above.

g. Design criteria - The complete package of performance data which describes the simulated air vehicle and its flight.

h. Instructor - The instructor defined herein is located exterior to the cockpit.

4. REQUIREMENTS

4.1 Major components. The major components to be provided are:

a. Simulator cockpit motion system.

b. Operating and maintenance controls and displays for the motion and control loading systems.

c. Access stairway.

4.1.1 Interface requirements. Certain interface requirements are specified herein between the motion system and control loading system, and between the motion system and access stairway. Complete detailed performance requirements are specified herein for the motion system.

4.2 Performance characteristics. A simulator cockpit motion system shall be provided. Within the performance envelope of the motion system, motion onset and attitude cues shall be provided to the simulator crew members which correspond in direction to the cues which would be perceived by the crew members in the actual aircraft under the flight conditions being simulated.

4.2.1 Simulated motions. The motion system shall perform smoothly and without hunting at all times. The motion system movement shall be determined by computer computations based upon six degrees of aircraft freedom. The simulated motions shall optimize the tracking of the total acceleration vector of the simulated aircraft crew station, including changes in magnitude and direction. The frequency of occurrence of new acceleration cues shall be maximized; during position washout, new acceleration cues shall be accepted in any direction constrained only by the position and velocity limits of the system, and the threshold of perception of the crewmember(s). The motion system shall provide cues in multiple degrees of freedom simultaneously, as demanded by the flight equations of motion. Acceleration cues provided to the cockpit shall not exceed the acceleration of the actual aircraft under the same conditions. Spurious motion and washout motion shall at no time be noticeable to crew members.

4.2.1.1 Motion activity. As a minimum, the following motions shall be simulated: stalls, slides, slips, dives, climbs, banks, spins, rolls, the release of missiles or stores, touchdown attitude and impact, movements corresponding to brake application, landing gear strut dynamics, ground dynamics including runway rumble, movements corresponding to landing gear extension or retraction, and movements corresponding to center of gravity or center of pressure movement. Motion cues shall be provided for buffet and vibration dynamics at frequencies approximating actual aircraft frequencies, subject to the criteria of the paragraph on frequency response. Steady-state simulated aircraft pitch attitude shall result in a constant corresponding pitch attitude of the cockput. Entry into a coordinated turn shall result in roll and other related motoions to provide the onset cues; if the coordinated turn is held, the cockpit shall imperceptibly return to a roll angle of zero degrees.

4.2.1.2 Rough air. The effects of rough air and wind buffet shall be simulated in the motion system in all appropriate degrees of freedom.

4.2.2 Payload weight. Performance requirements shall be met at the normal operating weight (cockpit plus all on-board personnel) plus 4000 pounds. If a visual system is provided concurrently with the simulator, performance requirements shall be met at the normal operating weight (cockpit, visual system, plus all on-board personnel) plus 1000 pounds.

4.2.3 Worst-case maneuvers. The motion system shall smoothly and correctly perform the worst-case flow maneuvers the simulated vehicle and its pilot will demand, such as a rapid series of demanding flight maneuvers.

4.2.4 Step response. Motion system response to a step input shall occur in less than 0.05 second. Motion system response to a cockpit control input shall occur in accordance with design criteria.

4.2.5 Excursions and velocities. The motion system shall perform to the criteria shown in table I and table II. Each degree of freedom is defined individually with respect to a nonmoving coordinate system centered at the centroid of the platform in its neutral position. The displacement requirements of table I are nonsimultaneous requirements; therefore, the motion system must satisfy only one set of requirements (case) at a time. However, the excursion envelope about the neutral operating position shall allow simultaneous movements to the limits specified below:

Vertical	±6 inches
Lateral	±6 inches
Longitudinal	±6 inches
Pitch	±4 degrees
Roll	±4 degrees
Yaw	±4 degrees

Table I. Excursion Requirements.

Vertical 1/	±34 inches
Lateral	±34 inches
Longitudinal	±34 inches
Pitch 1/	±25 degrees
Roll	±20 degrees
Yaw	±20 degrees

1/ Deviations from geometric neutral are permissible for these cases; however, total excursion (68 inches vertical and 50 degrees pitch) shall be maintained.

Table II. Velocity Requirements.

Vertical	24 inches per second
Lateral	24 inches per second
Longitudinal	24 inches per second
Pitch	20 degrees per second
Roll	20 degrees per second
Yaw	20 degrees per second

4.2.6 Acceleration and acceleration onset. The motion system shall meet the following minimum criteria, as a 0.2-second cue capability:

Movement	Onset Acceleration Rate	Maximum Acceleration
Vertical	±4g/sec	±0.8g
Lateral	±3g/sec	±0.6g
Longitudinal	±3g/sec	±0.6g
Pitch	300 degrees/sec^2/sec	±60 deg/sec^2
Roll	300 deg/sec^2/sec	±60 deg/sec^2
Yaw	300 deg/sec^2/sec	±60 deg/sec^2

The above requirements shall be met from the neutral operating position of the motion system.

4.2.7 Frequency response. The closed loop performance of the motion system, as measured from the command input to the position load to response of the motion platform, shall comply with the following:

Frequency Range (Hz)	Maximum Phase Shift (Degrees)	Motion Platform Position (Maximum dB)
0.1 - 0.5	15^{o}	±2 dB
0.5 - 1.0	40^{o}	±4 dB
1.0 - 1.7	90^{o}	±8 dB
1.7 - 5.0	Not applicable	Perceptible cue

The above criteria apply to each degree of freedom.

4.2.7.1 Natural frequencies. The lowest natural frequency of the motion system shall be greater than 5.0 Hertz. Design provisions shall be made to avoid activation of any natural frequency greater than 5.0 Hertz.

4.2.8 Damping. The platform response in each degree of freedom to a square wave input of 5 percent of maximum voltage at 0.2 Hertz (without washout) shall show no overshoot.

4.2.9 Smoothness. Friction shall not induce any spurious acceleration transient greater than 0.04g peak at the pilot station with any or all of the rams being driven with a sinusoidal input signal of 10 percent of the maximum voltage at a frequency of 0.5 Hertz.

4.2.10 Stability. For any static position or constant velocity, there shall be no instabilities in the motion system or its servomechanisms which impart load accelerations greater than 0.015g.

4.2.11 Static accuracy. Static error between actual and commanded platform position shall be less than 1.0 percent of full scale.

4.2.12 Crosstalk. Crosstalk between separate servomechanisms shall not exceed 2.0 percent of the amplitude of the offending servo.

4.2.13 Drifts. Over any continuous operating period of twelve hours, the position drift in any servo shall not exceed 1.0 percent of its bi-polar full scale.

4.2.14 Synchronization. Cues provided by the motion system shall be properly synchronized with cues from other simulator systems such as G-seats, G-suits, aural systems, visual system, and cockpit displays. There shall be no noticeable time, position, velocity, or acceleration error between motion system cues and other cues.

4.3 Design and construction

4.3.1 Hydraulic and electromechanical design. The motion system shall be controlled electrically and powered hydraulically. It shall consist of a self-contained, fully-integrated system of controls, reservoir, pumps, distribution system, accumulators, manifolds, heat exchanger, and other necessary components.

4.3.1.1 Hydraulic pumps. All pumps shall be of the pressure-compensated, variable displacement type. A separate pump shall be utilized for control loading; this pump shall supply flow through its own distribution lines from the pump area to the vicinity of the motion base. The control loading system shall normally be independent and separate from the motion system; however, a manual cross-over network from the motion supply shall be provided to allow operation of the control loading systems when the control loading pump is inoperative.

4.3.1.2 Hydraulic system action. During normal operation, cavitation shall not occur in the pump, control valves, or other components of the hydraulic system. The pressure pulses caused by the pump shall not excite resonance; nor shall the motion system excite resonance in the simulator or any portion thereof. Transient pressure pulses, such as may be caused by rapid closing of a valve, shall not be perceptible to crewmembers, nor shall such pulses cause damage to the hydraulic system. Chattering of valves shall not occur.

4.3.1.3 Hydraulic system maintenance design. The design shall incorporate adequate provisions for maintenance operations, including sampling, draining, cleaning, bleeding, and filling the hydraulic system. Shut-off valves and drain ports shall be provided as necessary for maintenance operations. The design shall include provisions for removal and replacement of any hydraulic actuator, including maintenance jack support and ease of access. Permanent hydraulic line connectors shall be used wherever possible. Leakproof separable connectors shall be used as necessary to assist in sound installation and maintenance features.

4.3.1.4 Hydraulic accumulators. Inert gas accumulators shall be provided as necessary to assist flow requirements during worst-case maneuvers. Accumulator pressure drop during worst-case on-line maneuvers shall not exceed 30 percent of the supply pressure.

4.3.1.5 Heat exchangers. Heat exchangers utilizing liquid as a cooling medium shall be regenerative, closed-cycle systems. Air-cooled heat exchangers shall be designed to operate with a maximum inlet air temperature of 110°F. The contractor shall provide all heat exchangers; however, the procuring agency may elect to incorporate the cooling requirements of the hydraulic system into the facility heat exchanger system.

4.3.1.6 Protection from hydraulic fluid. Spray shields and drip pans shall be provided as necessary to collect leaking hydraulic fluid. Electrical components and cabling and hydraulic components shall be positioned to prevent any damage to cabling as a result of fluid leaks. The number of leaks and flow rate of leaking fluid shall be minimized; the procuring agency shall judge the acceptability of the tightness of the system.

4.3.1.7 High temperature, fluid level, and low pressure. Hydraulic fluid shall have a minimum flashpoint temperature of 200°F and shall be compatible with MIL-H-5606. An oil temperature sensing gauge shall be provided with either an audio or visual overtemperature warning device. Excessive oil temperature shall automatically activate shut-down of the hydraulic system. A reservoir of adequate capacity with a sight gauge shall be provided. Automatic shut-down of the motion system shall occur if the fluid level is too low for normal operation, or if system pressure drops below a predetermined value.

4.3.1.8 Pressure relief valves and filters. Pressure relief valves shall be installed in the system and shall open if the maximum design working pressure is exceeded. Replaceable or recleanable filters shall be provided throughout the system as necessary to ensure reliable operation. Coarse filters (25 micron maximum) shall be installed near the pump pressure outlets. Fine filters (10 micron maximum) shall be placed upstream of servo control valves. Additional filters shall be provided as necessary to ensure reliable operation, including special means to clean pump contaminants. All filters shall be euqipped with differential pressure switches to provide a remote indication (at the maintenance control panel) that the filter needs servicing. Additionally, a local differential-pressure indicator shall be provided on each filter assembly. If the filter is equipped with a bypass, the differential pressure switch will actuate before the bypass opens (i.e., at a lower differential pressure). All filters shall be easily accessible for servicing.

4.3.1.9 Maintenance access. The motion system design shall permit ease of access for maintenance duties. A skid-proof walkway with railing shall be provided which permits personnel to walk completely around the cockpit.

4.3.1.10 Access stairway. A powered access stairway (or ramp) shall be provided for personnel entry and exit onto the motion platform. Interlocks shall be provided to ensure th.. the access stairway is physically removed from the operating envelope of the motion system when the motion system is engaged. The system shall be designed to prevent a physical collision between the access stairway and motion system. The system shall be designed to prevent injury to personnel by movements of the access stairway. The access stairway shall be equipped with handrails and coated with anti-skid material. In the event of total electrical power failure, means shall be provided to automatically move the access stairway to the cockpit egress position. When the motion system moves to the settled position, the access stairway shall automatically move to the egress position. The stairway design shall be adapted to the facility. A limited view of the cockpit motion system by personnel entering the cockpit is desired.

4.3.2 Motion and control loading system controls and indicators. In addition to adhering to the principles of MIL-STD-1472, the control and indicator system shall comply with the following paragraphs.

4.3.2.1 Instructor station. Controls shall be provided at the instructors' station to engage or disengage the motion system and access stairway.

4.3.2.2 Cockpit. The following controls shall be provided within the cockpit:

4.3.2.2.1 Cockpit control. A momentary action, push type "Motion Consent" switch or other suitable means shall be provided in the cockpit to assure crew readiness for motion engagement. Engagement of the motion system from the instructors' station shall be possible only when the "Consent" switch is simultaneously being depressed by the crewmember.

4.3.2.3 Maintenance and control panel. A maintenance control panel shall be provided and located within view of the motion system. The panel shall provide controls to drive each actuator to any safe position desired by the operator. On-off and engage-disengage controls shall be provided. An "Emergency Stop" switch shall be located on the panel to shut down the system. A key-operated "Mode" switch shall be provided for "maintenance" or "normal" operation. The "normal" position shall deactivate maintenance panel controls, except for the "emergency stop" control. The "maintenance" position shall deactivate instructor motion controls returning full control to the maintenance operator. Other interlocks shall be provided as necessary for safe, convenient operation. Visual status indicators of pressure, fluid contamination, filters, temperature, control positions and other pertinent information shall be provided.

4.3.2.4 Pump room controls. Controls and indicators shall be provided on a control panel located in the pump room to permit local control and monitoring of the pumps, as well as power-on and power-off operation. These controls and indicators shall be similar to those on the maintenance control panel. Quantitative pressure and temperature displays shall be provided for the control loading pump(s) and motion system pump(s). Interlocks shall be provided as necessary for safe, convenient operation.

4.4 Safety. Mechanical, electrical and hydraulic protective devices shall be provided to protect crewmembers, operating personnel, observers, and maintenance personnel from injury.

4.4.1 Design safety factors. All hydraulic system components shall be pressure-rated at least 50 percent higher than the maximum working pressure of the system. The design of all load-carrying structural members shall provide a minimum safety factor of four times yield strength under simultaneous conditions of worst case configuration and worst-case dynamic loads. Mechanical or hydraulic energy-absorbing devices shall be provided to absorb the greatest kinetic energy the system can develop if runaway occurs.

4.4.2 Rapid motion. At no time shall either the motion system or the cockpit controls unexpectedly move. "Freezing" or release from a simulator computer "freeze" condition shall not result in rapid motion system movement, even if cockpit control movements have been made during the "freeze" state. Engaging the motion system shall result in a non-rapid low-velocity transition from the settled position to the normal operating position in less than 15 seconds. Other computer-controlled changes in motion system position such as transition to initial conditions, automatic demonstration modes, etc., shall not be rapid. A rapid motion system movement shall be defined as any movement(s) which imparts an acceleration greater than 0.10g to the crewmember(s).

4.4.2.1 Abrupt motion. Disengagement of the motion system shall not result in abrupt motion system movement. Abrupt motion system movement shall not occur when the pumps are deactivated unexpectedly, nor if line power failure or fluctuation occurs. An abrupt motion system movement shall be defined as any movement(s) which imparts an acceleration greater than 0.40g to the crewmember(s).

4.4.3 Motion limits. Hydraulic actuators shall be equipped with electrical limit switches to automatically disengage the motion system if ram overtravel occurs. In addition, angular limit sensing devices shall be provided to automatically disengage the motion system if rotational overtravel occurs.

4.4.4 Settling of motion system. When the motion system is shut down or disengaged, the cockpit shall return to a settled, level egress position. The cockpit shall not assume unusual attitudes or undergo unusual movements during descent to a settled position. A passive mechanical-hydraulic system shall be provided and shall automatically activate settling of the motion system when an electrical power failure occurs.

4.4.5 Electrical interlock. The motion system shall be protected by automatic interlocks so that proper sequencing for power-up or power-down is assured and so that abnormal conditions inhibit the application of power to the motion platform. As a minimum, interlocks shall be provided on the cockpit canopy, cockpit door, entrance gate, access stairway, and within pressure pads on the entrance. It shall not be possible to engage the motion system unless all interlocks are in a safe position; the motion system shall then be engaged when the proper controls are activated. The reverse sequence (control switch is activated, interlocks moved to safe position, motion system responds) shall not occur. If the interlock circuit is broken when the motion system is engaged, the motion system shall immediately disengage. Subsequent engagement of the system must adhere to normal control switch procedures.

4.4.6 Emergency egress. In the event of an emergency, it shall be possible to rapidly open the canopy (or cockpit door) from the inside and from the outside. The time required for the motion system and access stairway to move to the egress position shall not exceed 8 seconds.

4.4.7 Warning signs. Illuminated warning signs shall be provided at all entrances to the motion system or cockpit areas. These signs shall provide warnings appropriate to the location of the entrance. Warning lights shall be provided as necessary to alert personnel that the motion pumps are on, and the motion system is engaged.

4.4.8 Safety barrier. A safety barrier shall be provided and shall surround the motion system base to the degree necessary. Gates shall be provided as necessary for personnel and equipment ingress. The design shall be adapted to the facility.

4.4.9 Geometry. The motion system design shall not permit the system to achieve unsafe orientations or attitudes, for any, and all combinations of actuator positions.

4.4.10 Failures. Worst-case failures shall not impose more than ±2.5g on the cockpit. Special attention shall be paid to the cases of an actuator(s) reaching its full extension at maximum velocity, and a sudden null or reverse signal being applied to a servomechanism(s) while the actuator(s) is in mid-stroke at maximum velocity. A design goal shall be to safely return the motion platform to the settled egress position subsequent to any failure.

4.5 Analyses. The contractor shall conduct analyses as necessary to assure the performance, safety, and integrity of the system.

4.5.1 Floor loading. The contractor shall provide a detailed design of the motion system support structure and design criteria to the procuring agency for use in building site installation preparation. The reaction mass composition, tie-down means, and complete interface shall be included in the support design. The support structure shall be designed for installation in soil of 1500 pounds per square foot bearing capacity. Leveling of the motion system within a tolerance of ±1/3 inch between adjacent pads shall be solely the responsibility of the contractor.

4.5.2 Noise. The contractor shall analyze the intensity and frequency spectrum of noise emanating from motion system pumps. If the noise level requires ear protective devices, the contractor shall recommend such devices to the procuring agency. Noise data shall be provided to the procuring agency for use in design of pump room soundproofing.

4.5.3 Structural analyses. A complete structural analysis shall be conducted. Copies of structural analyses shall be submitted to the procuring agency.

4.5.4 Performance analyses. Analyses shall be conducted as necessary to verify that the proposed system meets all requirements. Copies of performance analyses shall be submitted to the procuring agency.

Custodians:
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